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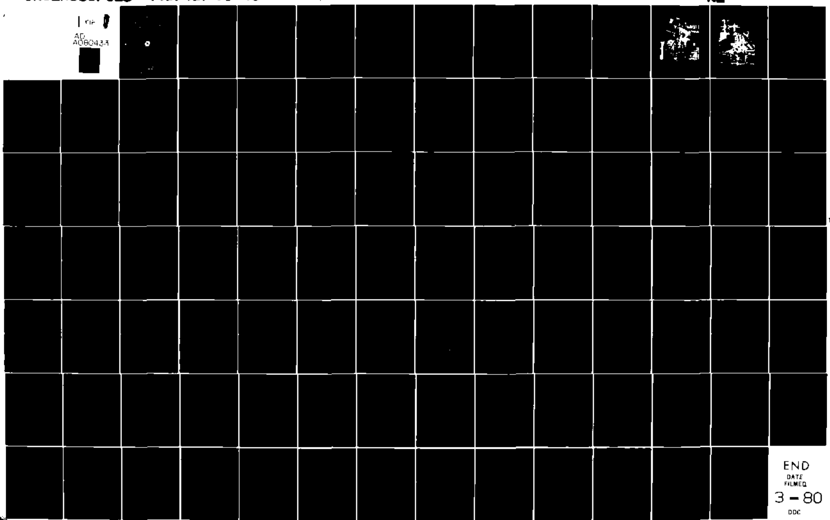

Report No. FAA-NA-79-40

EXHAUST EMISSIONS CHARACTERISTICS FOR A GENERAL AVIATION LIGHT-AIRCRAFT TELEDYNE CONTINENTAL MOTORS (TCM) GTSIO-520-K PISTON ENGINE

Eric E. Becker

DECEMBER 1979

FINAL REPORT

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Prepared for

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16. Abstract

The Teledyne Continental Motors (TCM) GTSIO-520-K engine (S/N220015) was tested at the National Aviation Facilities Experimental Center (NAFEC) to develop an exhaust emissions data base. This data base consists of current production baseline emissions characteristics, lean-out emissions data, effects of leaning-out the fuel schedule on cylinder head temperatures, and data showing ambient effects on exhaust emissions and cylinder head temperatures. The engine operation with it. current full-rich production fuel schedule could not meet the proposed Environmental Protection Agency (EPA) standard for carbon monoxide (CO) and unburned hydrocarbons (HC) under sea level standard-day conditions. The engine did, however, meet the proposed EPA standard for oxides of nitrogen (NO_x) under the same sea level conditions. The results of engine testing under different ambient conditions (essentially sea level standard day to sea level hot day) are also presented and these results show a trend toward higher levels of emissions output for CO and HC while producing slightly lower levels of NO_x.

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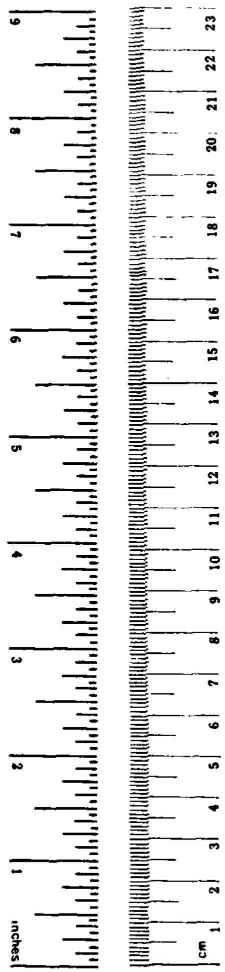
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

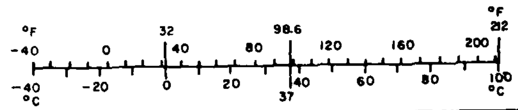
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

PURPOSE.

General aviation piston engine exhaust emission tests were conducted at the National Aviation Facility Experimental Center (NAFEC) for the following reasons:

1. Determine and establish total exhaust emissions characteristics for a representative group of current production general aviation piston engines.

2. Determine the effects of leaning-out of the fuel metering system on exhaust emissions.

3. Verify the acceptability of test procedures, testing techniques, instrumentation, etc.

4. Determine reductions in operating limits and safety margins resulting from fuel system adjustments/modifications evaluated for improved piston engine exhaust emissions characteristics.

BACKGROUND.

Beginning in 1967, Congress enacted a series of laws which added environmental considerations to the civil aviation safety, control, and promotional functions of the Federal Aviation Administration (FAA). This legislation was in response to the growing public concern over environmental degradation. Thus, the FAA was committed to the development, evaluation, and execution of programs designed to identify and minimize the undesirable environmental effects attributable to aviation.

In accordance with the Clean Air Act Amendments of 1970, the Environmental Protection Agency (EPA) established emission standards and outlined test procedures when it issued EPA rule part 87 in January 1973. The Secretary of Transportation, and therefore the FAA, was charged with the responsibility for issuing regulations to implement this rule and enforcing these standards.

Implementation of this rule was contingent on the FAA's finding that safety was not impaired by whatever means was employed to achieve the standards. For this reason, the FAA undertook a program, subsequent to the issuance of the EPA emission standards in July 1973, to determine the feasibility of implementation, verify test procedures, and validate test results.

There was concern that the actions suggested in order to comply with the EPA emission standards, such as operating engines at leaner mixture settings during landing and takeoff cycles, might compromise safety and/or significantly reduce engine operating margins. Therefore, the FAA contracted with Avco Lycoming and Teledyne Continental Motors (TCM) to select engines that they considered typical of their production, test these engines as normally produced

to establish a baseline emissions data base, and then alter (by lean-out adjustments) the fuel schedule and ignition timing to demonstrate methods by which the proposed EPA limits could be reached. In the event that hazardous operating conditions were indicated by the manufacturer's tests, independent verification of data would be necessary. Therefore, it was decided to duplicate the manufacturer's tests at NAFEC to provide the needed verification and expand the emissions data base through independent testing.

This report presents the NAFEC test results for the Teledyne Continental Motors (TCM) GTSIO-520-K piston engine (S/N220015). It should be noted that since the time of these tests, the EPA has rescinded the promulgated piston engine standards (reference 1). This work is reported upon herein in the same light as it would have been if the requirements were still in effect.

DISCUSSION

DESCRIPTION OF TELEDYNE CONTINENTAL MOTORS GTSIO-520-K ENGINE.

The GTSIO-520-K engine tested at NAFEC is a turbo supercharged fuel injected, horizontally opposed engine with a nominal 520 cubic inch displacement (cid), rated at 435 brake horsepower (bhp) for a nominal brake specific fuel consumption (bsfc) of 0.70. This engine is designed to operate on 100/130 octane aviation gasoline (appendix A--Fuel Sample Analysis of NAFEC Test Fuel). The vital statistics for this engine are provided in table 1.

TABLE 1. TCM GTSIO-520-K ENGINE

No. of Cylinders	6
Cylinder Arrangement	HO
Max. Engine Takeoff Power (HP, RPM)	435,3400
Bore and Stroke (in.)	5.25 x 4.00
Displacement (cu. in.)	519.54
Weight, Dry (lbs)--Basic Engine	614
Propeller Drive	Geared
Fuel Grade--Octane Rating	100/130
Compression Ratio	7.5:1
Max. Cylinder Head Temperature Limit (°F)	460
Max. Allowable Exhaust Gas Temperature (°F)	1650
Drive Ratio	0.67:1

DESCRIPTION OF TEST SET-UP AND BASIC FACILITIES.

For the NAFEC sea level static tests, the engines were installed in the propeller test stand shown in figures 1 and 2. This test stand was located in the NAFEC General Aviation Piston Engine Test Facility. The test facility provided the following capabilities for testing light aircraft piston engines:

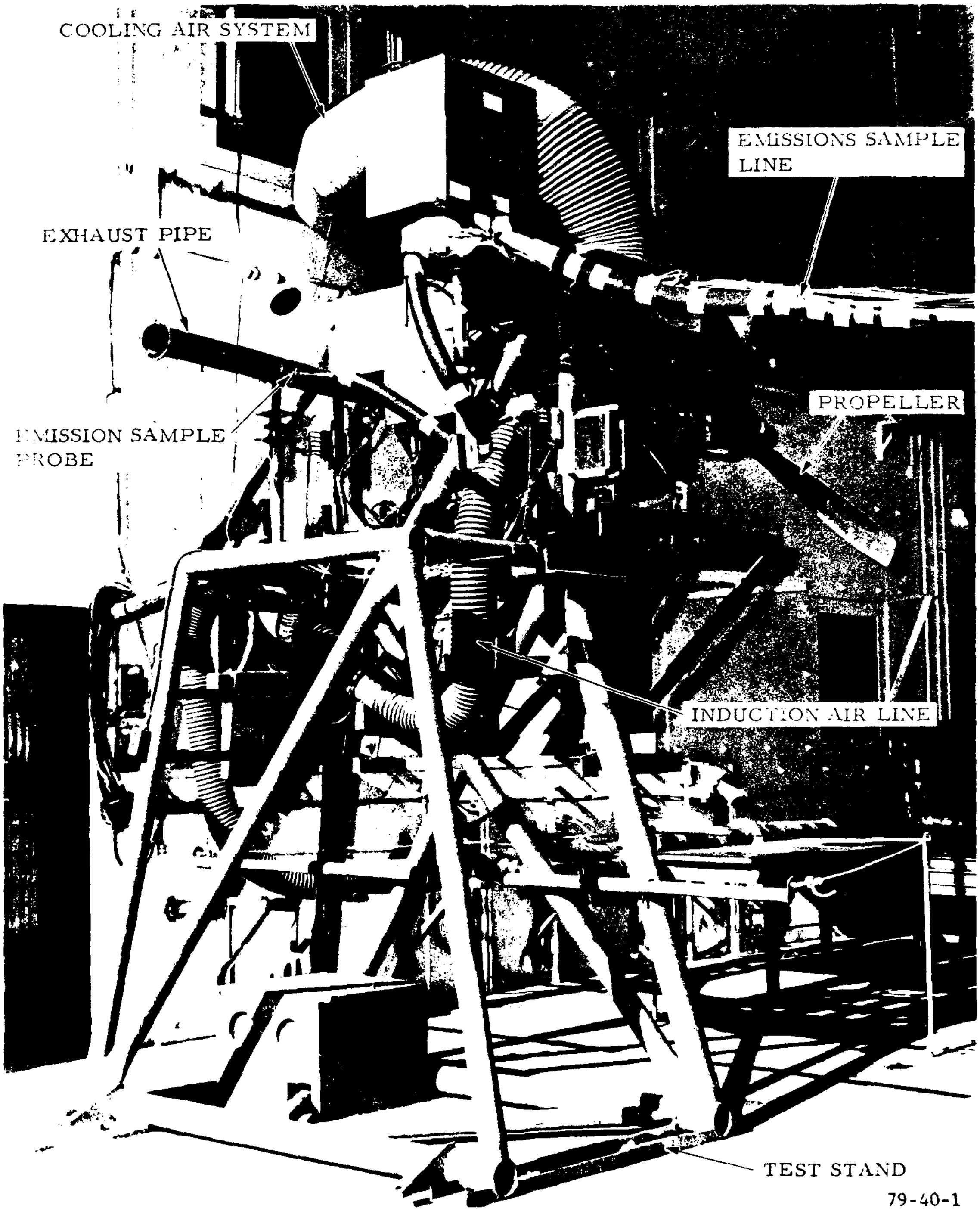


FIGURE 1. SEA LEVEL PROPELLER TEST STAND--TCM GTSIO-520-K PISTON ENGINE INSTALLATION--EMISSIONS TESTING

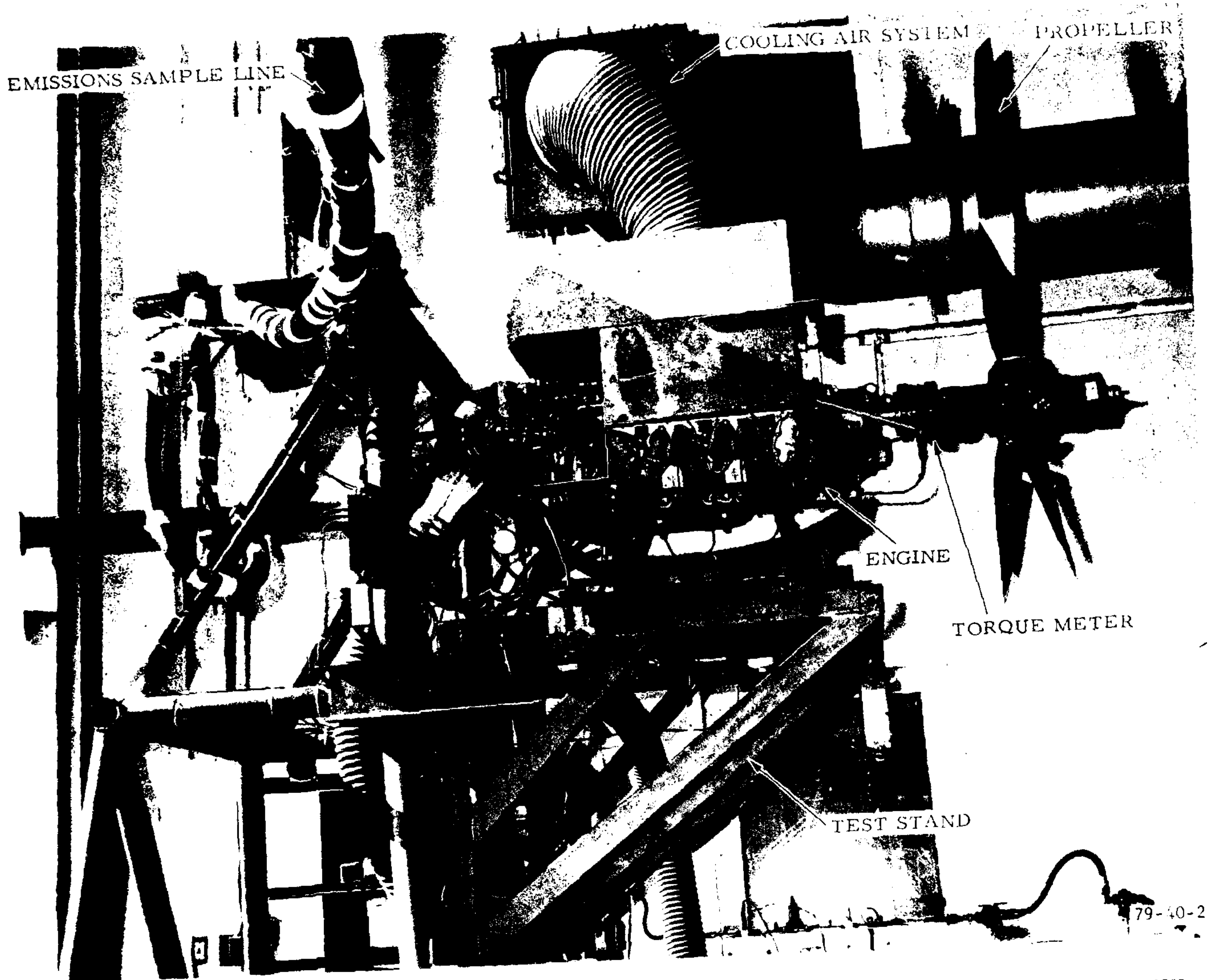


FIGURE 2. TCM GTSIO-520-K PISTON ENGINE INSTALLATION-NAFEC GENERAL AVIATION PISTON ENGINE TEST FACILITY

(1) Two basic air sources--dry bottled and ambient air
(2) Ambient temperatures (20 to 140 degrees Fahrenheit (°F))
(3) Nominal sea level pressures (28.50 to 31.50 inches of mercury absolute (inHgA)
(4) Humidity (specific humidity--0 to 0.020 lb of water (H_2O) vapor/lb dry air)
(5) Fuel (100/130 octane aviation gasoline--a dedicated 5,000-gallon tank)

DESCRIPTION OF AIR INDUCTION SYSTEM AND AIRFLOW COMPUTATIONS.

The airflow system (induction system) utilized at NAFEC for testing light-aircraft piston engines is illustrated in figure 3. This system incorporated a redundant airflow measuring system for accuracy and reliability. In the high-flow measuring section NAFEC utilized a 4.0-inch orifice and an Autronics air meter (model 100-750S). The capability of this high-flow system ranged from 800 to 4,000 pounds per hour with an estimated tolerance in flow accuracy of ±2 percent. The low-flow measuring section utilized a small 1.375-inch orifice and an Autronics air meter (model 100-100S). The capability of this system ranged from 80 to 800 pounds per hour with an estimated tolerance in flow accuracy of ±3 percent. The size of the basic air duct was 8.0 inches (inside diameter) for the high-flow system and 2.0 inches (inside diameter) for the low-flow system.

The airflow was computed from the orifice differential pressure and induction air density using the following equation:

$$Wa\ (\text{total}) = (1891)\ (C_f)\ (d_o)^2\ \ (.03609)(\Delta P_\rho)^{1/2} \quad \text{(Reference 2)}$$

ΔP = inH_2O (differential air pressure)
ρ = lb/ft^3 (induction air density)
d_o = inches (orifice diameter)
C_f = flow coefficient for orifice (nondimensional)
1891 = conversion constant for airflow in pounds per hour (lb/h).

For the 4.0-inch orifice this equation simplifies to:

$$Wa\ (\text{total}) = 3621.14\ (\Delta P_\rho)^{1/2}$$

For the 1.375-inch orifice this equation simplifies to:

$$Wa\ (\text{low flow}) = 472.03\ (\Delta P_\rho)^{1/2}$$

DESCRIPTION OF FUEL FLOW SYSTEM.

The fuel flow system utilizied during the NAFEC light-aircraft piston engine emission tests incorporated rotameters and turboflow meters. The high-flow section incorporated a rotameter in series with a high-flow turbometer, while the low-flow section incorporated a low-flow turbometer in series with a low-flow rotameter. The high-flow system was capable of measuring fuel flows from 50 lb/h up to 500 lb/h with an estimated tolerance of ±1.0 percent.

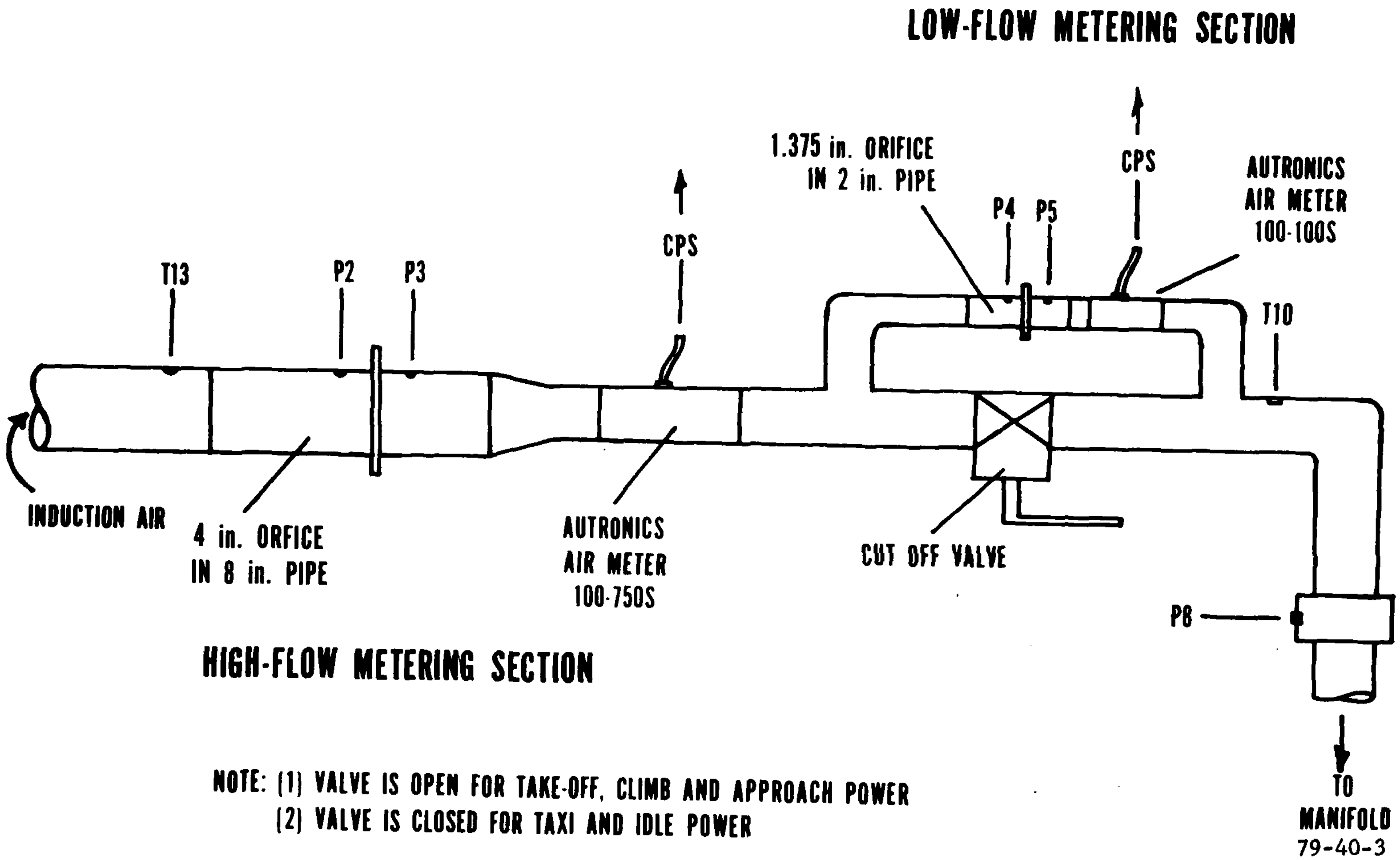


FIGURE 3. NAFEC AIR INDUCTION (AIRFLOW MEASUREMENT) SYSTEM FOR LIGHT-AIRCRAFT PISTON ENGINE EMISSION TESTS

The low-flow system was capable of flow measurements ranging from 0-50 lb/h with an estimated tolerance of ± 2.0 percent. Figure 4 illustrates the NAFEC fuel flow system in schematic form.

DESCRIPTION OF COOLING AIR SYSTEM.

The NAFEC piston engine test facility also incorporated a system which provided cooling air (see figure 1) to the engine cylinders. The engine mounted in the test stand was enclosed in a simulated nacelle, and cooling air was provided to this enclosure from an external source. The cooling air temperature was maintained within $\pm 10°$ F of the induction air supply temperature for any specified set of test conditions. This not only minimized variations in temperature but also minimized variations in the specific weight of air for all test conditions. All of the basic cooling air tests with the GTSIO-520-K engine were conducted with differential cooling air pressure of 4.0 inH_2O. During taxi mode tests, the cooling air differential pressure was approximately equal to 0 inH_2O.

DESCRIPTION OF TEST PROCEDURES AND EPA STANDARDS.

The data presented in this report were measured while conducting tests in accordance with specific landing and takeoff (LTO) cycles and by modal lean-out tests. The basic EPA LTO cycle is defined in table 2.

The FAA/NAFEC contract and in-house test programs utilized an LTO cycle which was a modification of the table 2 test cycle. Table 3 defines this modified LTO cycle which was used to evaluate the total full-rich emission characteristics of light-aircraft piston engines.

TABLE 2. EPA FIVE-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min.)	Power (%)	Engine Speed (%)
1	Taxi/idle (out)	12.0	*	*
2	Takeoff	0.3	100	100
3	Climb	5.0	75-100	*
4	Approach	6.0	40	*
5	Taxi/idle (in)	4.0	*	*

*Manufacturer's Recommended

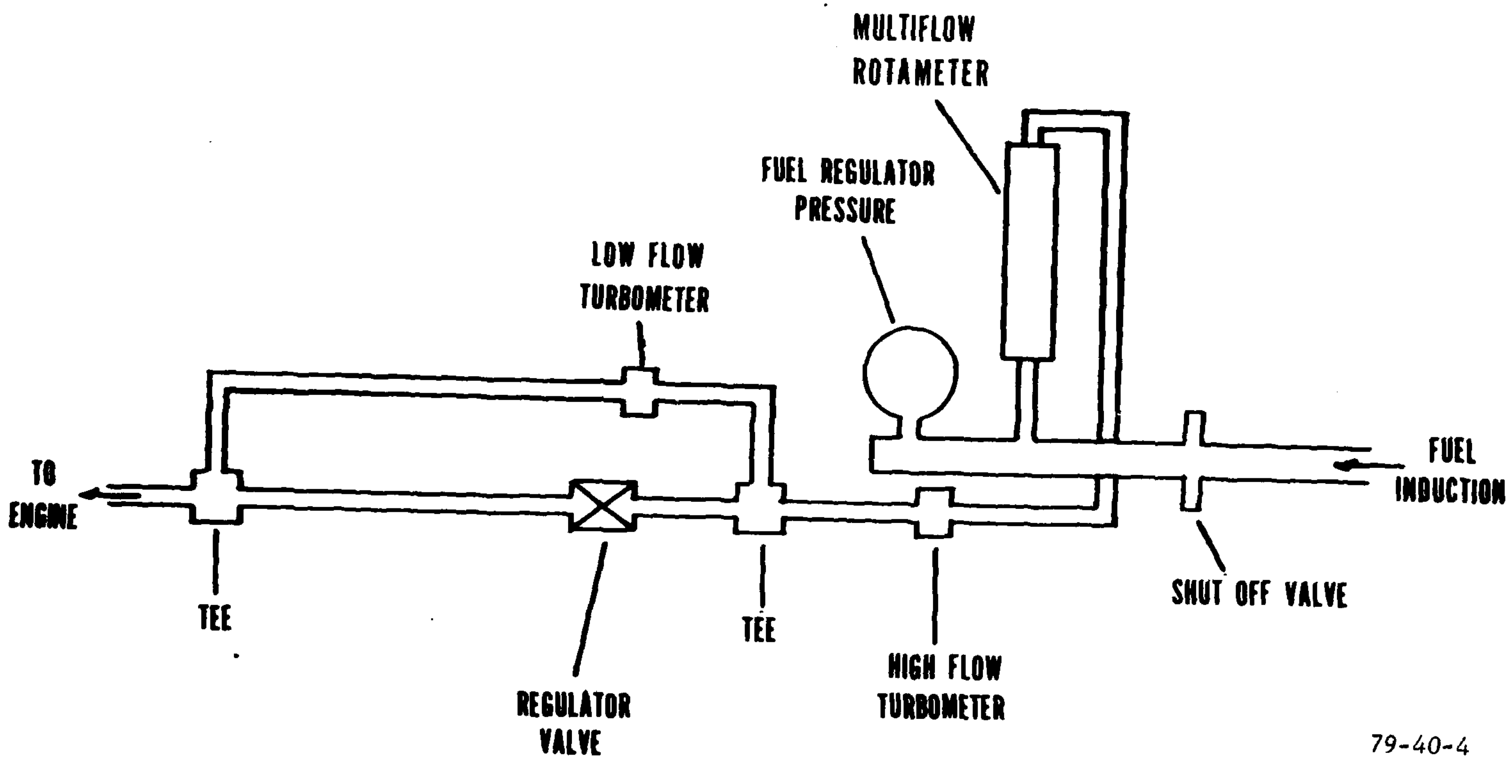


FIGURE 4. NAFEC FUEL FLOW SYSTEM FOR LIGHT-AIRCRAFT PISTON ENGINE EMISSION TESTS

TABLE 3. FAA/NAFEC SEVEN-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min.)	Power (%)	Engine Speed (%)
1	Idle (out)	1.0	*	*
2	Taxi (out)	11.0	*	*
3	Takeoff	0.3	100	100
4	Climb	5.0	80	*
5	Approach	6.0	40	*
6	Taxi (in)	3.0	*	*
7	Idle (in)	1.0	*	*

*Manufacturer's Recommended

An additional assessment of the test data clearly indicated that further evaluations of the general aviation piston exhaust emissions must be analyzed with the climb mode emissions at 100-percent and 75-percent power setting (tables 4 and 5). This would then provide the basis for a complete evaluation of test data and permit a total assessment of the proposed EPA standard based on LTO cyclic tolerances. Tests were conducted at these settings.

TABLE 4. MAXIMUM FIVE-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min.)	Power (%)	Engine Speed (%)
1	Taxi (out)	12.0	*	*
2	Takeoff	0.3	100	100
3	Climb	5.0	100	100
4	Approach	6.0	40	*
5	Taxi (in)	4.0	*	*

*Manufacturer's Recommended

TABLE 5. MINIMUM FIVE-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min)	Power (%)	Engine Speed (%)
1	Taxi (out)	12.0	*	*
2	Takeoff	0.3	100	100
3	Climb	5.0	75	*
4	Approach	6.0	40	*
5	Taxi (in)	4.0	*	*

*Manufacturer's Recommended

The EPA Standards (reference 1) that were evaluated during this program were:

Carbon Monixide (CO)—0.042 lb/cycle/rated BHP
Unburned Hydrocarbon (HC)—0.0019 lb/cycle/rated BHP
Oxides of Nitrogen (NO_x)—0.0015 lb/cycle/rated BHP

DESCRIPTION OF EMISSIONS MEASUREMENT SYSTEM (REFERENCE 3).

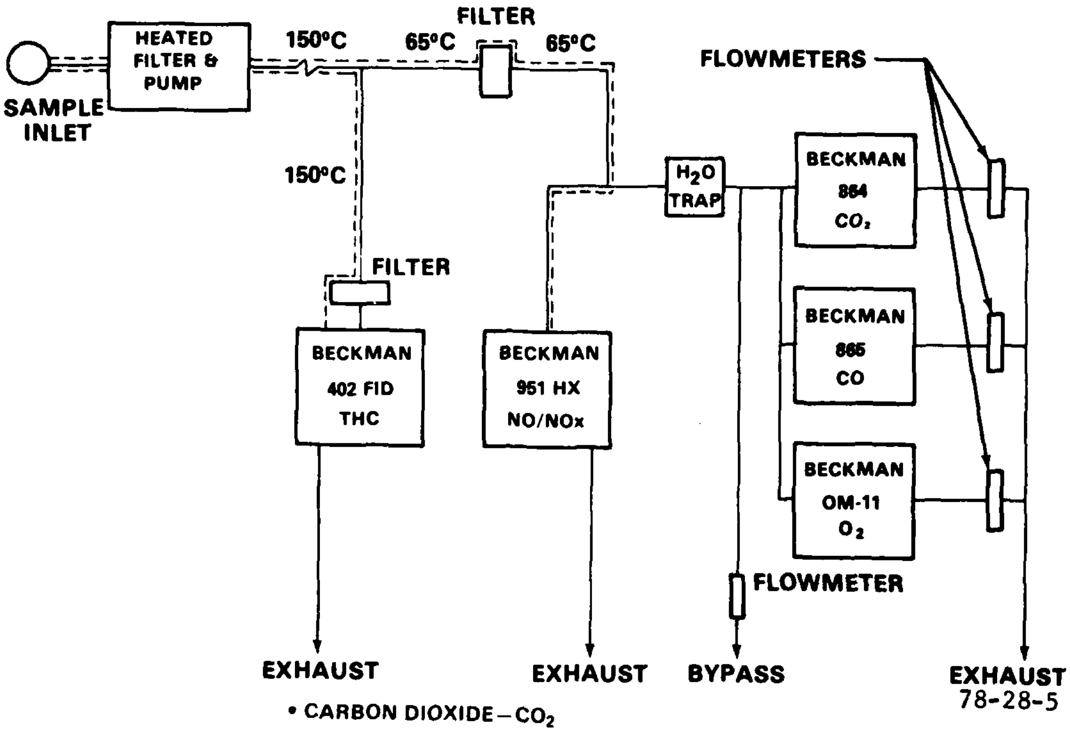
EMISSION ANALYZERS. The instrumentation used to monitor the exhaust emissions from general aviation piston engines was basically the same as that recommended by EPA, but with a number of modifications and additions to enhance the reliability and accuracy of the system. A schematic of the emissions measurement system is shown in figure 5.

EMISSION INSTRUMENTATION ACCURACY/MODIFICATION. The basic analysis instrumentation utilized for this system is explained in the following paragraphs.

Carbon Dioxide. The carbon dioxide (CO_2) subsystem is constructed around a Beckman model 864-23-2-4 nondispersive infrared analyzer (NDIR). This analyzer has a specified repeatability of ± 1 percent of full scale for each operating range. The calibration ranges on this particular unit are: Range 1, 0 to 20 percent; Range 3, 0 to 5 percent. Stated accuracy for each range is, therefore, ± 0.2 and ± 0.05 percent, respectively.

Carbon Monoxide. The subsystem used to measure carbon monoxide (CO) is constructed around a Beckman model 865-X-4-4-4 NDIR. This analyzer has a specified repeatability of ± 1 percent of full scale for ranges 1 and 2 and ± 2 percent of full scale for range 3.

Range 1 has been calibrated for 0 to 20 percent by volume, range 2 for 0 to 1,000 parts per million (ppm), and range 3 for 0 to 100 ppm. The wide-range capability of this analyzer is made possible by using stacked sample cells which in effect give this analyzer six usable ranges when completely calibrated.



- CARBON DIOXIDE – CO_2
  - NONDISPERSIVE INFRARED (NDIR)
  - RANGE 0-20%
  - REPEATABILITY ± 0.2% CO_2
- CARBON MONOXIDE – CO
  - NDIR
  - RANGE 0-20%
  - REPEATABILITY ± 0.2% CO
- TOTAL HYDROCARBONS – THC
  - FLAME IONIZATION DETECTOR (FID)
  - RANGE 0-150,000 ppm_c
  - MINIMUM SENSITIVITY 1.5 ppm_c
  - LINEAR TO 150,000 ppm_c
- **OXIDES OF NITROGEN – NO_X**
  - CHEMILUMINESCENT (CL)
  - RANGE 0-10,000 ppm
  - MINIMUM SENSITIVITY 0.1 ppm
- **OXYGEN – O_2**
  - POLARAGRAPHIC
  - RANGE 0-100%
  - REPEATABILITY 0.1% O_2
  - RESPONSE 200 ms

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FIGURE 5. SCHEMATIC OF EMISSIONS MEASUREMENT SYSTEM AND ITS MEASUREMENT CHARACTERISTICS

Effects of interfering gases, such as CO_2 and water vapor, were determined and reported by the factory. Interferences from 10 percent CO_2 were determined to be 12 ppm equivalent CO, and interferences from 4 percent water vapor were determined to be 6 ppm CO equivalent. Even though the interference from water vapor is negligible, a condenser is used in the CO/CO_2 subsystem to eliminate condensed water in the lines, analyzers, and flowmeters. This condensation would have decreased analyzer sensitivity and necessitated more frequent maintenance if it had been eliminated.

Total Hydrocarbons. The system that is used to measure total hydrocarbons is a modified Beckman model 402 heated flame ionization detector. This analyzer has a full-scale sensitivity that is adjustable to 150,000 ppm carbon with intermediate range multipliers 0.5, 0.1, 0.05, 0.01, 0.005, and 0.001 times full scale.

Repeatability for this analyzer is specified to be ±1 percent of full scale for each range. In addition, this modified analyzer is linear to the full-scale limit of 150,000 ppm carbon when properly adjusted. The two major modifications which were made to this analyzer were the installation of a very fine metering value in the sample capillary tube, and the installation of an accurate pressure transducer and digital readout to monitor sample pressure. Both of these modifications were necessary because of the extreme pressure sensitivity of the analyzer (figures 6 through 8). Correct instrument response depends on the amount of sample passing through a capillary tube; as a result, if there is too high a sample flow, the analyzer response becomes nonlinear when a high concentration gas is encountered. Sample flow may be controlled by varying the pressure on this capillary or increasing the length of the capillary. On this analyzer, linearity to 50,000-ppm carbon was obtained by reducing the sample pressure to 1.5 pounds per square inch gauge (psig). However, the need for linearity to 120,000-ppm carbon was anticipated. Further reduction of the sample pressure increased the noise level of the analyzer to an unacceptable level. In order to reduce the flow through the capillary without using a lower pressure, either the length or the resistance of the capillary had to be increased. The standard modification for this analyzer in order to limit flow is the installation of an additional length of capillary tubing. This procedure requires trial and error determination of proper capillary length and is a permanent modification that limits sensitivity at low hydrocarbon levels. By installing a metering valve in the capillary, flow could be selectively set at either low flow for linearity at high concentrations or high flow for greater sensitivity at low concentrations. Installation time was reduced by eliminating the cut-and-try procedure for determining capillary length.

The addition of a sensitive pressure transducer and digital readout to monitor sample pressure was needed since the pressure regulator and gauge supplied with the analyzer would not maintain the pressure setting accurately at low pressures. Using the digital pressure readout, the sample pressure could be monitored and easily maintained to within 0.05 inH_2O.

Oxides of Nitrogen. Oxides of nitrogen (NO_x) are measured by a modified Beckman model 951H atmospheric pressure, heated, chemiluminescent analyzer (CL). This analyzer has a full-scale range of 10,000 ppm with six intermediate ranges. Nominal minimum sensitivity is 0.1 ppm on the 10 ppm full-scale range.

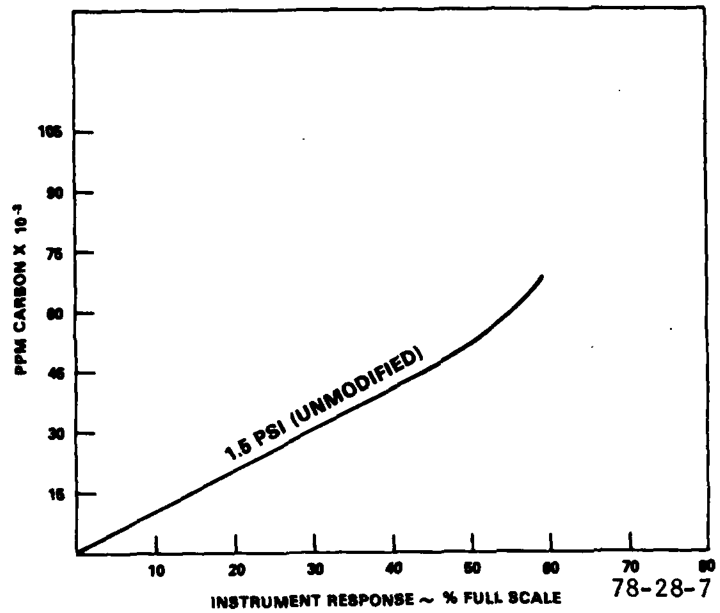

FIGURE 6. BECKMAN MODEL 402 THC ANALYZER (1.5 PSI UNMODIFIED)

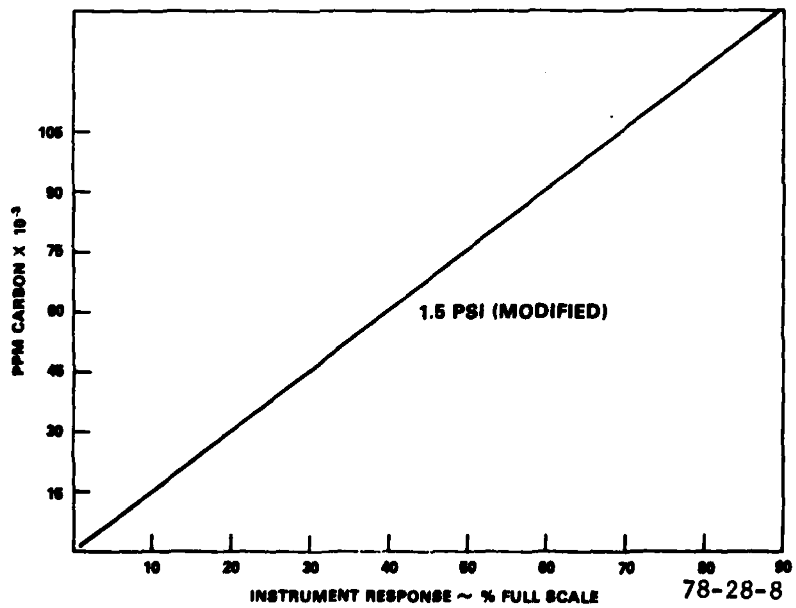

FIGURE 7. BECKMAN MODEL 402 THC ANALYZER (1.5 PSI MODIFIED)

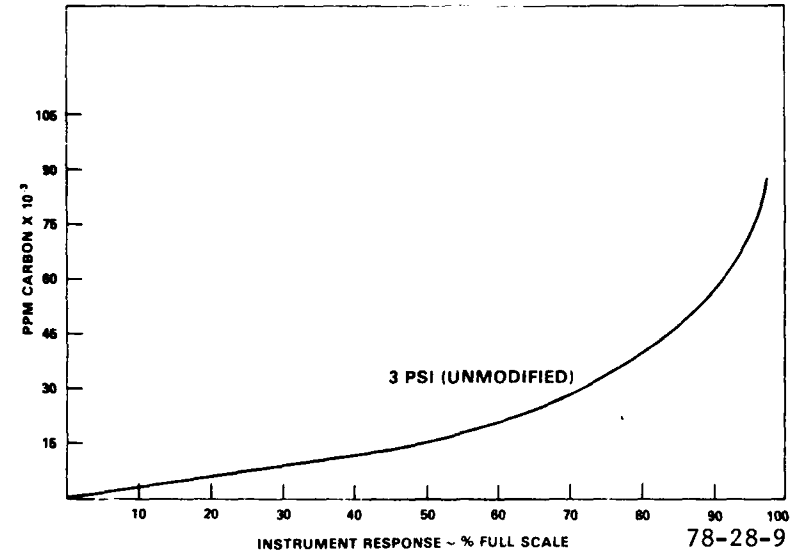

FIGURE 8. BECKMAN MODEL 402 THC ANALYZER (3 PSI UNMODIFIED)

The atmospheric pressure analyzer was chosen because of its simplicity, ease of maintenance, and compactness. Anticipated water vapor problems in the atmospheric pressure unit were to be handled by the heating of the internal sample train. Interference from CO_2 quenching, common in the atmospheric pressure type CL analyzer, was checked and found to be nonexistent.

A series of major modifications were performed by the manufacturer on this analyzer to insure compliance with specifications. One such modification was installed in order to maintain the temperature of the sample stream above the dew point of the sample gas. Originally this analyzer was specified to maintain a temperature of 140° F at all points in contact with the sample. After a survey of the 951H analyzers in use on FAA projects, it was determined that this temperature was not being achieved because the method used to heat the components was inadequate. A recommendation was made to the manufacturer to install a positive method of heating the sample tube compartment and reaction chamber that would be thermostatically controlled. In time, the modification was made, and this problem was eliminated. Increasing the temperature of the internal sample components eliminated the condensed water problem; however, the elevated temperature caused an instability in the photomultiplier tube output. Another recommendation was made to thermostatically control the temperature of this tube. This was accomplished by installing an electronic cooling jacket designed to maintain the photomultiplier tube at a constant temperature below the internal case temperature.

A further modification required was the addition of a flow control valve to adjust and balance the flow rate through the NO and NO_x legs. This valve

replaced a restrictor clamp that was used by the manufacturer to set the NO to NO_x flow balance. The problem that was encountered with this clamp was that it was not a positive method of adjusting the restriction on the capillary. The clamp compression was affected by the flexible material on which the clamp was mounted and the variable flexibility of the Teflon capillary as it was heated. This caused the restriction on the capillary to change with time and caused permanent deformation of the capillary allowing only an adjustment that would increase the restriction.

Oxygen Measurement. Oxygen (O_2) was measured by a Beckman model OM-11 oxygen analyzer. This analyzer uses a polagraphic type sensor unit to measure oxygen concentration. An advanced sensor and amplification system combine to give an extremely fast response and high accuracy. Specified response for 90 percent of final reading is less than 200 milliseconds (ms) with an accuracy of less than $\pm$0.1-percent O_2. The range of this unit is a fixed 0 to 100 percent O_2 concentration.

EMISSIONS INSTRUMENTATION MODIFICATION STATUS DURING THE TESTING OF THE GTSIO-520-K ENGINE. The tests conducted with the TCM GTSIO-520-K engine utilized the Beckman model OM-11 oxygen (O_2) analyzer and a prototype Beckman model 951H oxides of nitrogen (NO_x) analyzer.

All of the emissions and exhaust constituent-measuring instruments/analyzers incorporated the latest specified modifications described in this report.

DESCRIPTION OF SAMPLE HANDLING SYSTEM.

Exhaust samples are transported to the analysis instrumentation under pressure through a 35-foot-long, 3/8-inch o.d., heated, stainless steel sample line. The gas is first filtered and then pumped through this line by a heated Metal Bellows model MB-158 high temperature stainless steel sample pump. The pump, filter, and line are maintained at a temperature of 300° $\pm$4° F to prevent condensation of water vapor and hydrocarbons. At the instrument console, the sample is split to feed the hydrocarbon, oxides of nitrogen, and $CO/CO_2/O_2$ subsystems which require different temperature conditioning. The sample gas to the total hydrocarbon subsystem is maintained at 300° F while the temperature of remaining sample gas to the NO_x and $CO/CO_2/O_2$ system is allowed to drop to 150° F. Gas routed to the oxides of nitrogen subsystem is then maintained at 150° F, while the gas to the $CO/CO_2/O_2$ subsystem is passed through a 32° F condenser to remove any water vapor present in the sample. Flow rates to each analyzer are controlled by a fine-metering valve and are maintained at predetermined values to minimize sample transport and system response time. Flow is monitored at the exhaust of each analyzer by three 15-centimeter (cm) rotameters. Two bypasses are incorporated into the system to keep sample transport time through the lines and condenser to a minimum without causing adverse pressure effects in the analyzers.

DESCRIPTION OF FILTRATION SYSTEM.

Particulates are removed from the sample at three locations in the system, thereby minimizing downtime due to contaminated sample lines and analyzers (figure 5). Upstream of the main sample pump is a heated clamshell-type stainless steel filter body fitted with a Whatman GF/C glass fiber paper filter element capable of retaining particles in the 0.1 micron range. A similar

filter is located in the total hydrocarbon analyzer upstream of the sample capillary. A Mine Safety Appliances (MSA) type H ultra filter capable of retaining 0.3 micron particles is located at the inlet to the oxides of nitrogen and $CO/CO_2/O_2$ subsystems.

COMPUTATION PROCEDURES.

The calculations required to convert exhaust emission measurements into mass emissions are the subject of this section.

Exhaust emission tests were designed to measure CO_2, CO, unburned hydrocarbons (HC), NO_x, and exhaust excess O_2 concentrations in percent or ppm by volume. Mass emissions were determined through calculations utilizing the data obtained during the simulation of the aircraft LTO cycle and from modal lean-out data.

COMBUSTION EQUATION. The basic combustion equation can be expressed very simply:

Fuel + Air = Exhaust Constituents

An initial examination of the problem requires the following simplifying assumptions:

1. The fuel consists solely of compounds of carbon and hydrogen.

2. The air is a mixture of oxygen and inert nitrogen in the volumetric ratio of 3.764 parts apparent nitrogen to 1.0 part oxygen (see appendix B for additional details).

3. If a stoichiometric combustion process exists, the fuel and air are supplied in chemically correct proportions.

4. The fuel (which consists usually of a complex mixture of hydrocarbons) can be represented by a single hydrocarbon having the same carbon-hydrogen ratio and molecular weight as the fuel; usually C_8H_{17} as an average fuel.

Applying the above assumptions for stoichiometric conditions, a useful general reaction equation for hydrocarbon fuel is:

$$M_fC_8H_{17} + M_a\left(O_2 + 3.764N_2 + M_wH_2O\right) \rightarrow M_1CO_2 + M_3H_2O + M_5N_2 \qquad (1)$$

(References 4 and 5)

Where
M_f = Moles of Fuel
M_a = Moles of Air or Oxygen
M_1 = Moles of Carbon Dioxide (CO_2)
M_3 = Moles of Condensed Water (H_2O)
M_5 = Moles of Nitrogen (N_2) - Exhaust
$3.764M_a$ = Moles of Nitrogen (N_2) - In Air
M_aM_w = Moles of Humidity (H_2O) - In Air

The above equation is applicable to dry air when M_w is equal to zero.

From equation (1), and assuming dry air with one mole of fuel (M_f=1.0), the stoichiometric fuel-air ratio may be expressed as:

$$(F/A)_s = \frac{\text{Wt. Fuel}}{\text{Wt. Air Required}} = \frac{12.011\ (8) + 1.008\ (17)}{12.25\ \left[32.000 + 3.764(28.161)\right]} \qquad (2)$$

$$(F/A)_s = \frac{113.224}{12.25(137.998)} = 0.067$$

The mass carbon-hydrogen ratio of the fuel may be expressed as follows:

$$C/H = \frac{12.001(8)}{1.008(17)} = \frac{96.088}{17.136} = 5.607 \qquad (3)$$

The atomic hydrogen-carbon ratio is:

$$17/8 = 2.125 \qquad (4)$$

The stoichiometric fuel-air ratio may be expressed as a function of the mass carbon-hydrogen ratio of the fuel. The derivation of this equation is presented in reference 4.

$$(F/A)_s = \frac{C/H + 1}{11.5(C/H+3)} \qquad (5)$$

$(F/A)_s$ = 0.067 for a mass carbon-hydrogen ratio of 5.607

With rich (excess fuel) mixtures, which are typical for general aviation piston engines, some of the chemical energy will not be liberated because there is not enough air to permit complete oxidation of the fuel. Combustion under such conditions is an involved process. By making certain simplifying assumptions based on test results, the effect of rich mixtures may be calculated with reasonable accuracy.

For rich (excess fuel) mixtures, equation (1) will now be rewritten to express the effects of incomplete combustion:

$$M_fC_8H_{17} + M_a(O_2 + 3.764N_2 + M_wH_2O) \rightarrow M_1CO_2 + M_2CO + M_3H_2O + M_4H_2 +$$
$$M_5N_2 + M_6NO + M_7CH_4 + M_8O_2 + M_9C \qquad (6)$$

Since only a limited number of the exhaust constituents were measured during the testing of general aviation piston engines, the above equation can only be solved by applying certain expeditious assumptions and emperical data.

An important requirement was the accurate measurement of air and fuel flows. These parameters provide the data for determining engine mass flow (W_m), and with the aid of figure 9 (developed from reference 6), it is a simple computation to calculate the total moles (M_{tp}) of exhaust products being expelled by general aviation piston engine.

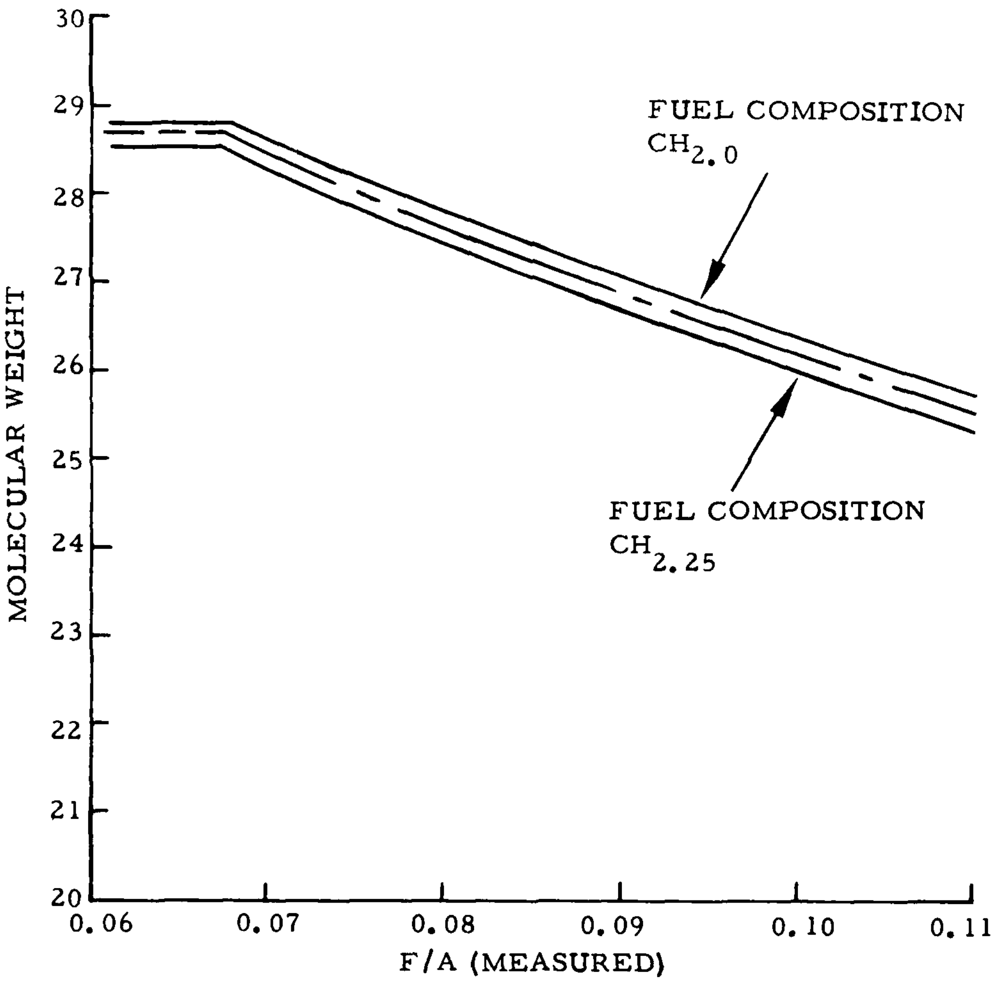

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FIGURE 9. EXHAUST GAS MOLECULAR WEIGHTS

$$(M_{tp}) = W_m \text{ (engine mass flow)} \div \text{(exh. mol. wt)} \quad (7)$$

Since the unburned hydrocarbons (HC) and oxides of nitrogen (NO_x) are measured wet, it becomes a very simple matter to compute the moles of HC and NO_x that are produced by light-aircraft piston engines.

$$M_7 \text{ (Moles of HC)} = (\text{ppm} \div 10^6) \times M_{tp} \quad (8)$$

$$M_6 \text{ (Moles of } NO_x) = (\text{ppm} \div 10^6) \times M_{tp} \quad (9)$$

If the dry products (M_{dp}) of combustion are separated from the total exhaust products (M_{tp}), it is possible to develop a partial solution for five of the products specified in equation 6.

This can be accomplished as follows:

The summation of the mole fractions $(MF)_d$ for dry products is

$$m_1 + m_2 + m_4 + m_5 + m_8 = 1.0000 \quad (10)$$

$m_1 = MF(CO_2) = \%CO_2$ (measured dry), expressed as a fraction

$m_2 = MF(CO) = \%CO$ (measured dry), expressed as a fraction

$m_4 = MF(H_2) = K_4$ (%CO) (see figure 10, also references 4, 5, and 6), expressed as a fraction

$m_8 = MF(O_2) = \%O_2$ (measured dry), expressed as a fraction

$m_5 = 1.0000 - (m_1 + m_2 + m_4 + m_8) = \%N_2$ (dry), expressed as a fraction (11)

Utilizing the nitrogen balance equation, it is now possible to determine the moles of nitrogen that are being exhausted from the engine.

$$M_5 = 3.764M_a - (M_6 \div 2);\ M_6 = \text{moles (NO)} \quad (12)$$

The moles of exhaust dry products (M_{dp}) may now be determined by dividing equation 12 by equation 11.

$$M_{dp} = M_5 \div m_5 \quad (13)$$

Using all the information available from equations (7), (8), (9), (10), (11), (12), and (13), it is now possible to determine the molar quantities for seven exhaust products specified in equation 6.

$$\text{Moles } (CO_2) = M_1 = m_1 \times M_{dp} \quad (14)$$

$$\text{Moles } (CO) = M_2 = m_2 \times M_{dp} \quad (15)$$

$$\text{Moles } (H_2) = M_4 = m_4 \times M_{dp} \quad (16)$$

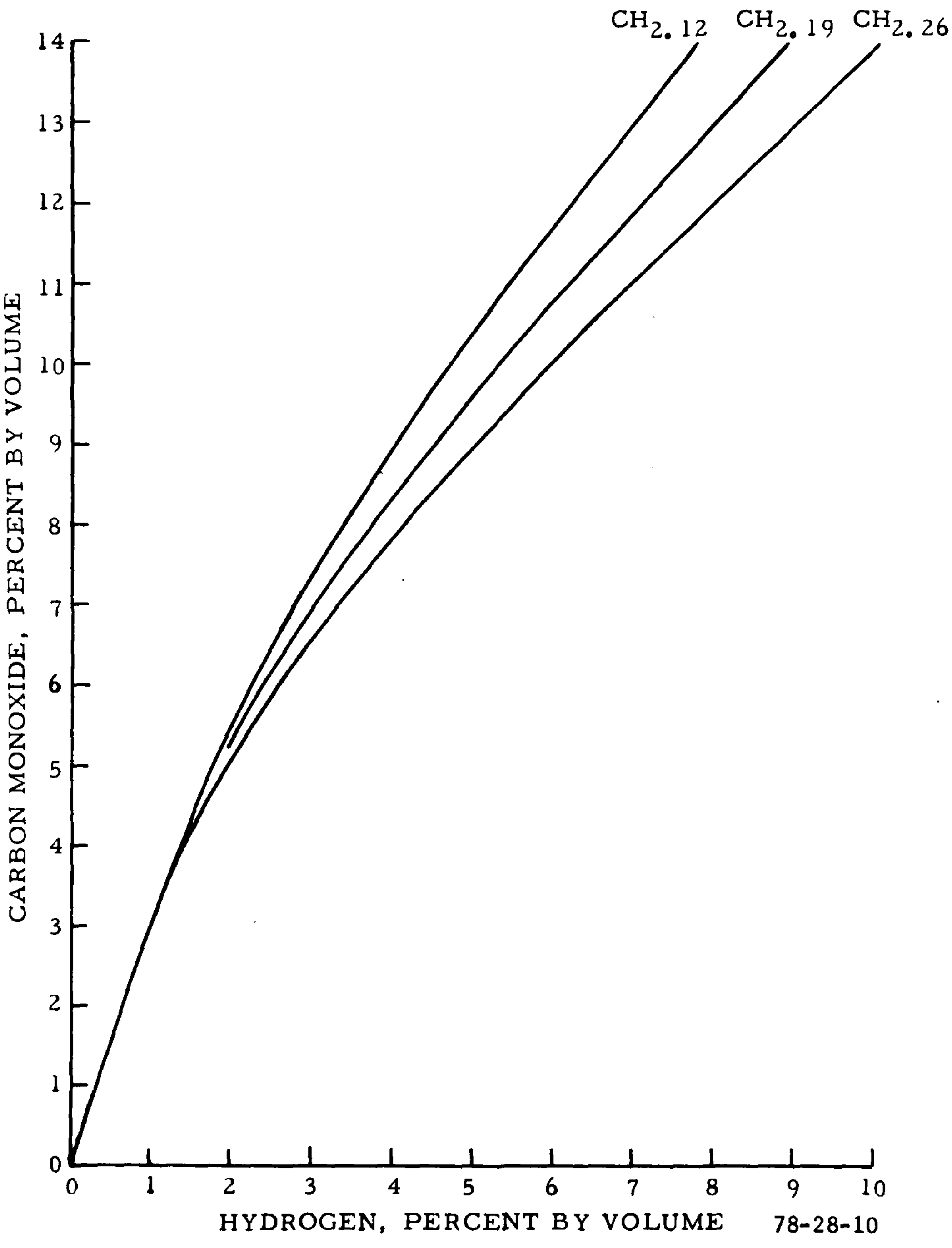

FIGURE 10. RELATION OF CARBON MONOXIDE AND HYDROGEN

$$\text{Moles } (N_2) = M_5 = m_5 \times M_{dp} \tag{17}$$

$$\text{Moles } (O_2) = M8 = m_8 \times M_{dp} \tag{18}$$

$$\text{Moles } (CH_4) = M_7 = (\text{ppm} \div 10^6) \times M_{tp} \tag{19}$$

$$\text{Moles } (NO) = M_6 = (\text{ppm} \div 10^6) \times M_{tp} \tag{20}$$

To determine M_3 (moles of condensed H_2O), it is now appropriate to apply the oxygen balance equation.

$$M_3 = M_a\ (2 + M_w) - (2M_1 + M_2 + M_6 + 2M_8) = \text{Moles } (H_2O) \tag{21}$$

The remaining constituent specified in equation 6 may now be determined from the carbon balance equation 22.

$$M_9 = 8M_f - (M_1 + M_2 + M_7) \tag{22}$$

A check for the total number of exhaust moles (M_{tp}), calculated from equation 9, may now be determined from equation 23.

$$M_{tp} = M_1 + M_2 + M_3 + M_4 + M_5 + M_6 + M_7 + M_8 + M_9 \tag{23}$$

$$\dot{m}_1 + \dot{m}_2 + \dot{m}_3 + \dot{m}_4 + \dot{m}_5 + \dot{m}_6 + \dot{m}_7 + \dot{m}_8 + \dot{m}_9 = 1.0000 \tag{24}$$

$$\dot{m}_1 = MF(CO_2) = M_1 \div Mtp$$

$$\dot{m}_2 = MF(CO) = M2 \div Mtp$$

$$\dot{m}_3 = MF(H_2O) = M_3 \div M_{tp}$$

$$\dot{m}_4 = MH(H_2) = M_4 \div M_{tp}$$

$$\dot{m}_5 = MF(N_2) = M_5 \div M_{tp}$$

$$\dot{m}_6 = MH(NO) = M_6 \div M_{tp}$$

$$\dot{m}_7 = MF(CH_4) = M_7 \div M_tp$$

$$\dot{m}_8 = MF(O_2) = M_8 \div M_{tp}$$

$$\dot{m}_9 = MF(C) = M_9 \div M_{tp}$$

The exhaust constituent mass flow rates may be computed in the following manner using each exhaust constituents molar constant with the appropriate molecular weight.

$$M_1 \times 44.011 = CO_2 \text{ in lb/h} \tag{25}$$

$$M_2 \times 28.011 = CO \text{ in lb/h} \tag{26}$$

$M_3 \times 18.016 = H_2O$ in lb/h (27)

$M_4 \times 2.016 = H_2$ in lb/h (28)

$M_5 \times 28.161 = N_2$ in lb/h (29)

$M_6 \times 30.008 = NO$ in lb/h (30)

$M_7 \times 16.043 = CH_4$ in lb/h (31)

$M_8 \times 32.000 = O_2$ in lb/h (32)

$M_9 \times 12.011 = C$ in lb/h (33)

The exhaust fuel flow (W_{fe}), based on exhaust constituents, can now be calculated on a constituent-by-constituent basis as follows:

$(M_1 + M_2 + M_9) \times 12.011 = \text{lb/h}$ (34)

$M_7 \times 16.043 = \text{lb/h}$ (35)

$(M_3 - M_a M_w) + M_4 \times 2.016$ (36)

$W_{fe} = (34) + (35) + (36) = \text{lb/h}$ (37)

In a similar manner the exhaust airflow (W_{ae}) can also be calculated on a constituent-by-constituent basis:

$M_1 \times 32.000 = \text{lb/h}$ (38)

$M_2 \times 16.000 = \text{lb/h}$ (39)

$(M_3 \times 16.000) + (M_a M_w \times 18.016) = \text{lb/h}$ (40)

$M_5 \times 28.161 = \text{lb/h}$ (41)

$M_6 \times 30.008 = \text{lb/h}$ (42)

$M_8 \times 32.000 = \text{lb/h}$ (43)

$W_{ae} = \Sigma\ (38) \leftrightarrow (43) = \text{lb/h}$ (44)

Using equations (37) and (44) it is now possible to determine a calculated fuel-air ratio on the basis of total exhaust constituents.

$(F/A)\text{calculated} = (37) \div (44)$ (45)

RESULTS

GENERAL COMMENTS.

General aviation pistion engine emission tests were conducted to provide the following categories of data:

1. Full-rich (or production fuel schedule) baseline data for each power mode specified in the LTO test cycle.

2. Lean-out data for each power mode specified in the LTO test cycle.

3. Data for each power mode specified in the LTO test cycle utilized cooling airflow $\Delta P = 4.0$ inH_2O at takeoff, climb, and approach powers. Taxi/idle mode cooling airflow ΔP was approximately equal to zero.

RESULTS OF BASELINE TESTS (LANDING-TAKEOFF CYCLE EFFECTS).

Based on an analysis of the factors affecting piston engine emissions, it can be shown that the mode conditions having the greatest influence on the gross pollutant levels produced by the combustion process are taxi, approach, and climb when using the LTO cycle defined in tables 3, 4, and 5. The five-mode LTO cycle shows that approximately 99 percent of the total cycle time (27.3-min) is attributed to these three modal conditions. Furthermore, the taxi modes (both out and in) account for slightly less than 59 percent of the total cycle time. The remainder of the time is almost equally apportioned to the approach and climb modes (22 and 18 percent, respectively).

As a result of these time apportionments, it was decided that an investigation and evaluation of the data should be undertaken to determine which mode(s) has the greatest influence on improving general aviation piston engine emissions. The subsequent sections of this report will show the exhaust emissions characteristics for a Teledyne Continental Motors (TCM) GTSIO-520-K engine (S/N220015) and what improvements are technically feasible within the limits of safe aircraft/engine operational requirements based on sea level propeller test stand evaluations conducted at NAFEC.

The first set of data to be presented and evaluated is the five-mode baseline runs conducted to establish the current production full-rich exhaust emissions characteristics of the GTSIO-520-K engine. These are summarized in tabular form in appendix C (see tables C-1 through C-20) and includes data that were obtained for a range of sea level ambient conditions, specified as follows:

Induction air temperature (T_i)	= 60° F to 135° F
Cooling air temperature (T_c)	= $T_i \pm 10°$ F
Induction air pressure (P_i)	= 29.70 to 31.15 inHgA
Induction air density (ρ)	= 0.0680 to 0.0770 lb/ft^3

Figure 11 presents five-mode baseline data in bargraph form (for different sea level ambient conditions). It also compares the total emissions characteristics of the GTSIO-520-K engine (current production configuration) with the proposed EPA standards as a function of percent of standard. The data that were utilized to develop figures 11, 12, and 13 are tabulated in appendix C and plotted in various forms for analysis and evaluation in figures C-1 through C-23.

RESULTS OF LEAN-OUT TESTS.

In the subsequent sections of this report, it will be shown what improvements can be achieved as a result of making lean-out adjustments to the fuel metering device: (1) taxi mode only, (2) taxi and approach modes combined, and (3) leaning-out the climb mode to "best power" or maximum cylinder head temperature in combination with taxi and approach mode leaning.

EFFECTS OF LEANING-OUT ON CO EMISSIONS. The test data obtained as a result of NAFEC testing the Teledyne Continental Motors GTSIO-520-K engine have been evaluated on the basis of leaning-out the taxi, approach, and climb modes while continuing the operation of the test engine at the production rich and lean limits in the takeoff mode. The results of leaning-out under this procedure are shown in bargraph form in figure 12.

When the taxi modes (out and in) were leaned-out from the production rich or lean limits to a fuel-air ratio of 0.075, but not lower than stoichiometric (F/A = 0.067) (see figure 12), CO emissions are reduced approximately 12 percent. However, adjustments to the taxi mode fuel schedule alone are not sufficient to bring the total five-mode LTO cycle CO emission level below the proposed federal standard.

Simultaneously, leaning-out both the taxi and approach modes to fuel-air ratios between 0.067 to 0.075 will result in additional improvements in CO emissions. In the case of operating the engine at production rich limits for takeoff and climb while operating taxi and approach at F/A = 0.075, the total five-mode LTO cycle CO emission level will be reduced approximately 34 percent as shown in figure 12.

Additional improvements in the total five-mode LTO cycle for CO emissions can be achieved, as shown in figure 12, if the engine is adjusted to operate at "best power" or maximum cylinder head temperature fuel-air ratios in the climb mode while operating the approach and taxi modes at F/A = 0.075 or lower (not lower than fuel-air ratio (F/A) = 0.067). The CO emission level will be reduced approximately 75 percent.

The preceding evaluation of CO emissions characteristics was based on the LTO cycle defined by table 5. However, the EPA five-mode LTO cycle defined by table 2 implies that the climb mode power levels range from 75 to 100 percent. The exhaust emissions produced will be drastically affected. Examination of the measured data produced at NAFEC shows that there is a significant difference in each engine's total LTO cycle emissions output when climbing at 100 percent power compared to climbing at 75-or 80-percent power. This

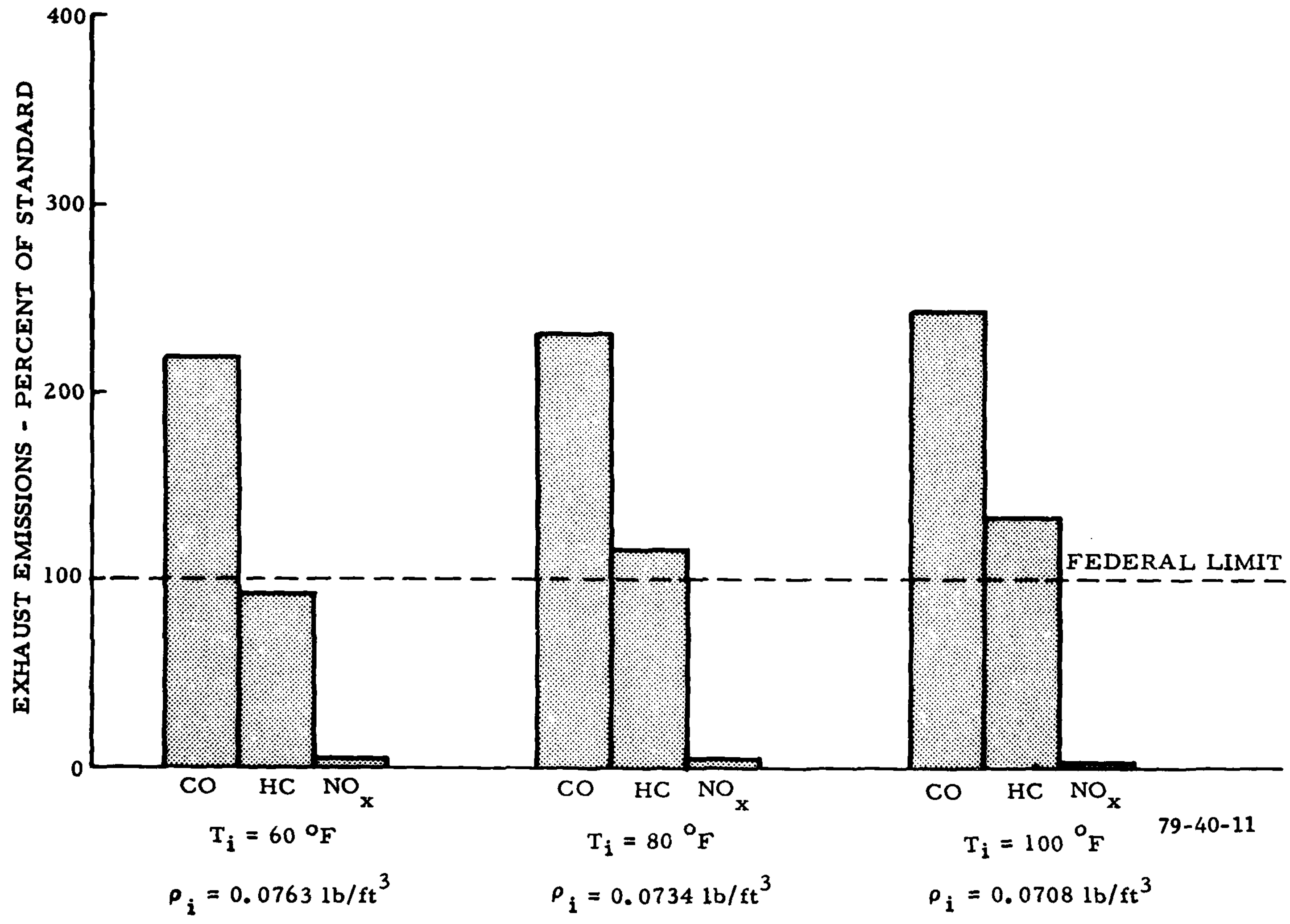

FIGURE 11. TOTAL EMISSIONS CHARACTERISTICS FOR A TCM GTSIO-520-K ENGINE OPERATING UNDER VARYING SEA LEVEL AMBIENT CONDITIONS--TABLE 5 MINIMUM FIVE-MODE LTO CYCLE--PRODUCTION RICH LIMIT FUEL SCHEDULE

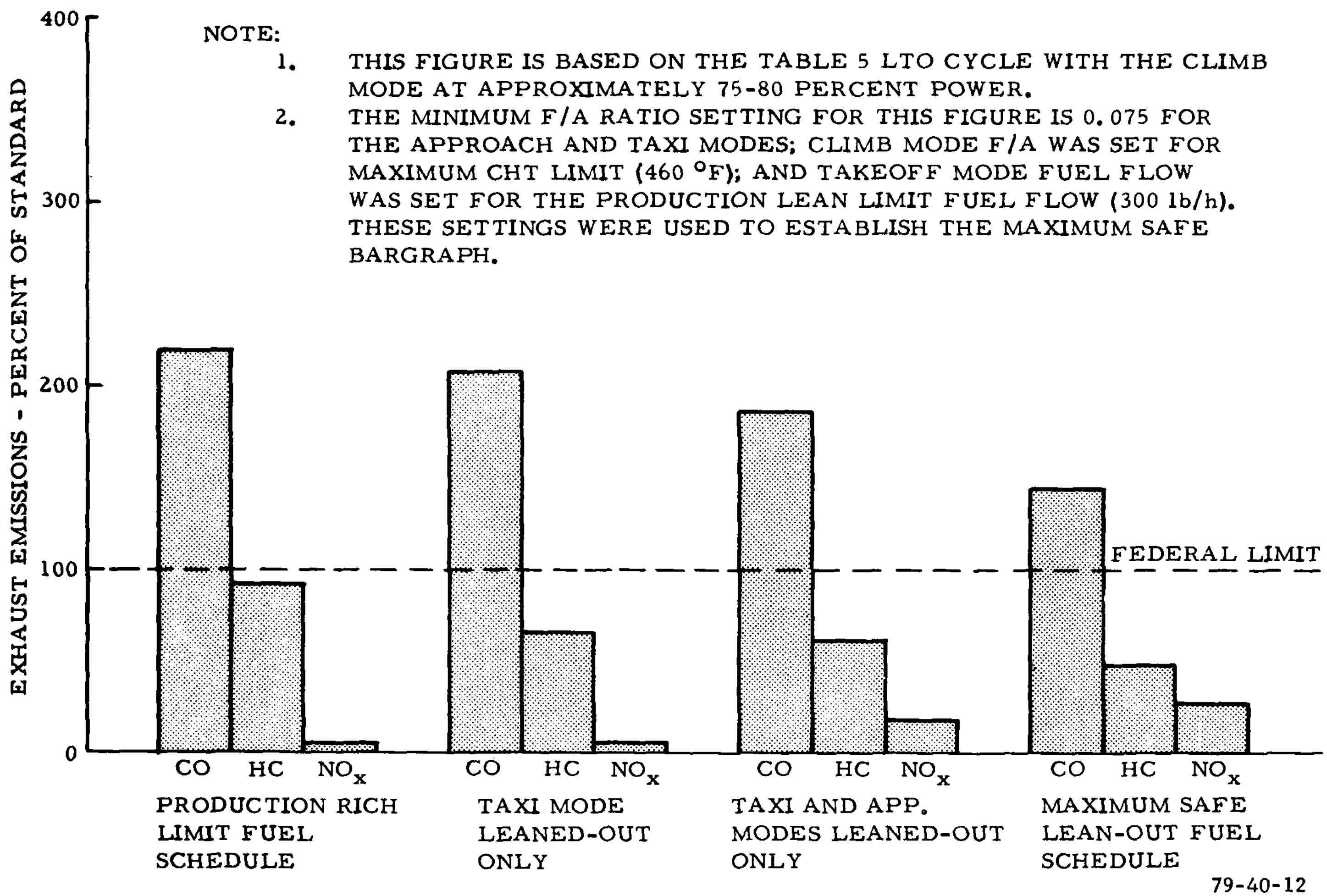

FIGURE 12. TOTAL EMISSIONS CHARACTERISTICS FOR A TCM GTSIO-520-K ENGINE WITH DIFFERENT FUEL SCHEDULE ADJUSTMENTS--SEA LEVEL STANDARD DAY--TABLE 5 MINIMUM FIVE-MODE LTO CYCLE

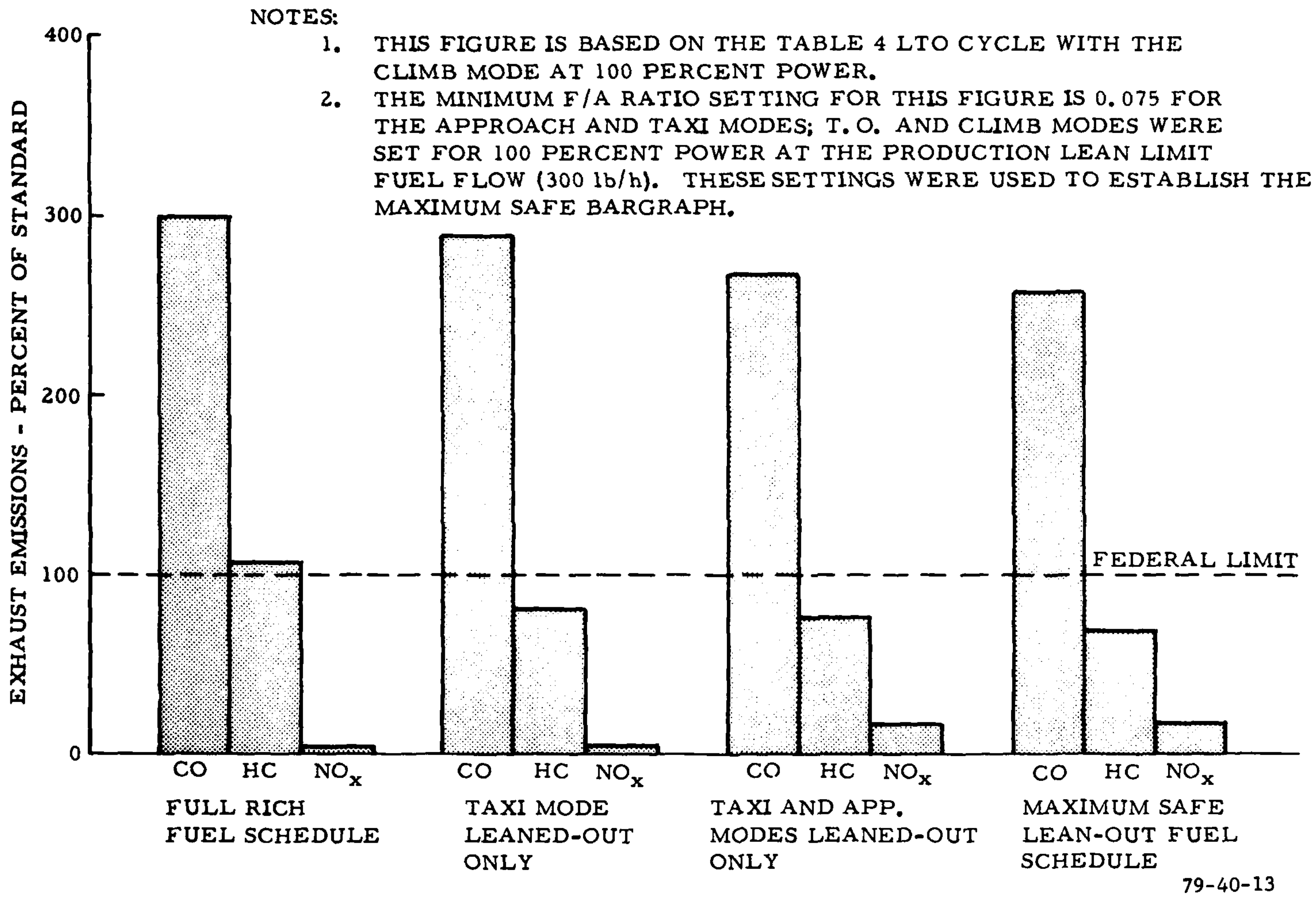

FIGURE 13. TOTAL EMISSIONS CHARACTERISTICS FOR A TCM GTSIO-520-K ENGINE WITH DIFFERENT FUEL SCHEDULE ADJUSTMENTS--SEA LEVEL STANDARD DAY--TABLE 4 MAXIMUM FIVE-MODE LTO CYCLE

data evaluation also shows that whereas a CO limit of 0.042 pounds per cycle per rated brake horsepower may be approximately achievable as described previously by using the LTO cycle defined by table 5; it is not achievable using an LTO cycle defined by table 4. When one considers the following safety considerations: (1) sea level, hot-day takeoff requirements with an aircraft at heavy gross weight and (2) altitude takeoff requirements with an aircraft at heavy gross weight, it would appear that the EPA 0.042 limit for CO is not realistic and cannot be complied with unless engine operational and safety limits are totally ignored.

Table 6 provides a summary of the NAFEC data which indicates what levels of improvement in CO emissions can be achieved by applying simple fuel management techniques (leaning-out by mixture control manipulations), albeit with drastically reduced margins between actual measured maximum cylinder head temperature (CHT) and the maximum CHT limit.

Example: Consider the engine installed in a sea level (SL.) propeller stand and operating with cooling air at a $\Delta P = 4.0$ inH_2O and the following critical test conditions:

1. Ambient conditions (pressure, temperature, and density)—SL. standard day
2. Fuel schedule—production rich setting
3. Power setting—100%
4. Measured max. CHT—420° F
5. Max. CHT limit—460° F
6. Margin— 5 minus 4 —40° F

If we now adjust this engine fuel schedule setting to best power or max. CHT limit (all other parameters constant based on above conditions), we now find the following changes take place:

1. CO emissions are improved approx. 75% (nominal)
2. Measured max. CHT increases 9.5% (from 420° F to 460° F)
3. Max. CHT limit—460° F
4. Margin— 3 minus 2 = 0° F
5. Reduction in margin (max. CHT)--(40+40) x 100 = 100.0%

Now, if we apply the above results to a SL. hot-day condition, we arrive at the following results:

Production Rich Limit Schedule (100% power)

1. Ambient conditions—SL. hot day (95° F)
2. Fuel schedule—production rich setting
3. Power setting—100% (nominal)
4. Measured max. CHT—435° F
5. Max. CHT limit—460° F
6. Margin— 5 minus 4 = 25° F

TABLE 6. SUMMARY OF EXHAUST EMISSIONS (CO) REDUCTION POSSIBILITIES FOR A TCM GTSIO-520-K ENGINE--SEA LEVEL STANDARD DAY (EXCEPT AS NOTED)--COOLING AIR $\Delta P = 4.0$ inH_2O

Modes	F/A	CO lb/Mode	Max Cht-°F	F/A	CO lb/Mode	Max Cht-°F	Max Cht-°F	Max Limit Cht-°F
1. Taxi	0.0900	6.400	350	0.0750	4.267			
2. Takeoff (100%)	0.1000	2.175	420	0.0965	2.070	440	455	460
3. Climb (100%)	0.1000	36.250	420	0.0965	34.500	440	455	460
4. Approach (40%)	0.0860	10.000	340	0.0750	6.000	350	375	460
5. lb/Cycle		54.825			46.837			
6. lb/Cycle/RBHP		0.1260			0.1077			
7. Federal Limit		0.042			0.042			
8. Diff. = 6-7		0.084			0.0657			
9. (8÷7) x 100		200.0			156.4			
10. % of STD = 9 + 100		300.0			256.4			
			This Column For S.L. Standard Day			This Column For S.L. Standard Day	This Column For S.L. Hot Day	
11. Taxi	0.0900	6.400	350	0.0750	4.267			
12. Takeoff (100%)	0.1000	2.175	420	0.0965	2.070	440	455	460
13. Climb (75%)	0.0960	22.917	410	0.0810	11.818	460	460	460
14. Approach (40%)	0.0860	10.000	340	0.0750	6.000	350	375	460
15. lb/Cycle		41.492			24.155			
16. lb/Cycle/RBHP		0.0954			0.0555			
17. Federal Limit		0.042			0.042			
18. Diff. = 16-17		0.0534			0.0135			
19. (18÷17) x 100		127.1			32.1			
20. % of STD = 19 + 100		227.1			132.1			

"Best Power Fuel Schedule" (100% Power) or Maximum Cylinder Head Temperature

1. Ambient conditions--sea level hot day
2. Fuel schedule--best power or maximum cylinder head temperature fuel schedule
3. Power setting--100% (nominal)
4. Measured max. CHT—460° F
5. Max. CHT limit--460° F
6. Margin-- 5 minus 4 = 0° F
7. Reduction in margin (max. CHT)—(20 ÷ 20) x 100 = 100.0%

EFFECTS OF LEANING-OUT ON HC EMISSIONS. The test data show that the TCM engine can be leaned-out sufficiently in the taxi mode to bring the unburned hydrocarbon emissions below the federal standard (figures 12 and 13). Additional leaning-out in the approach and climb modes provides added improvements, but is not required to produce HC emission levels below the federal standard.

EFFECTS OF LEANING-OUT ON NO_x EMISSIONS. Oxides of nitrogen emissions are not improved as a result of applying lean-out adjustments to the fuel metering devices. In fact, the NO_x levels are at their lowest when the engine is operating full rich as shown in figure 11. Test results have shown that if all the test modes (takeoff, climb, approach, and taxi) were leaned-out excessively (F/A=0.067), the NO_x emission level would exceed the federal standard.

The negative effect on NO_x emissions is one of the reasons why it was decided to evaluate and study the effects of adjusting/manipulating selected mode conditions rather than adopt the philosophy of adjusting all modes.

EFFECTS ON ALLOWABLE MAXIMUM CYLINDER HEAD TEMPERATURE. One of the major problems that occurs as an effect of leaning-out general aviation piston engines in order to improve emissions is the increase or rise in maximum cylinder head temperatures.

Most general aviation aircraft are designed to operate with cooling air pressure differentials of 4.0 inH_2O or less. The tests conducted with the TCM engine utilized 4.0 inH_2O as the basic cooling flow condition for the approach climb, and takeoff modes.

Data shown in tables C-1 through C-19 and plotted in figures 14 through 16 show the test results.

In summary it can be concluded that any attempts to lean-out current production-type horizontally opposed general aviation piston engines in the takeoff mode to F/A ratios lower than production lean limits will produce CHT's that are higher than the manufacturer's specified limit.

Any attempt to lean-out the climb mode to F/A ratios below best power will produce CHT's that are higher than the manufacturer's specified limit. This will become particularly acute under hot-day takeoff and climb conditions at sea level or altitude.

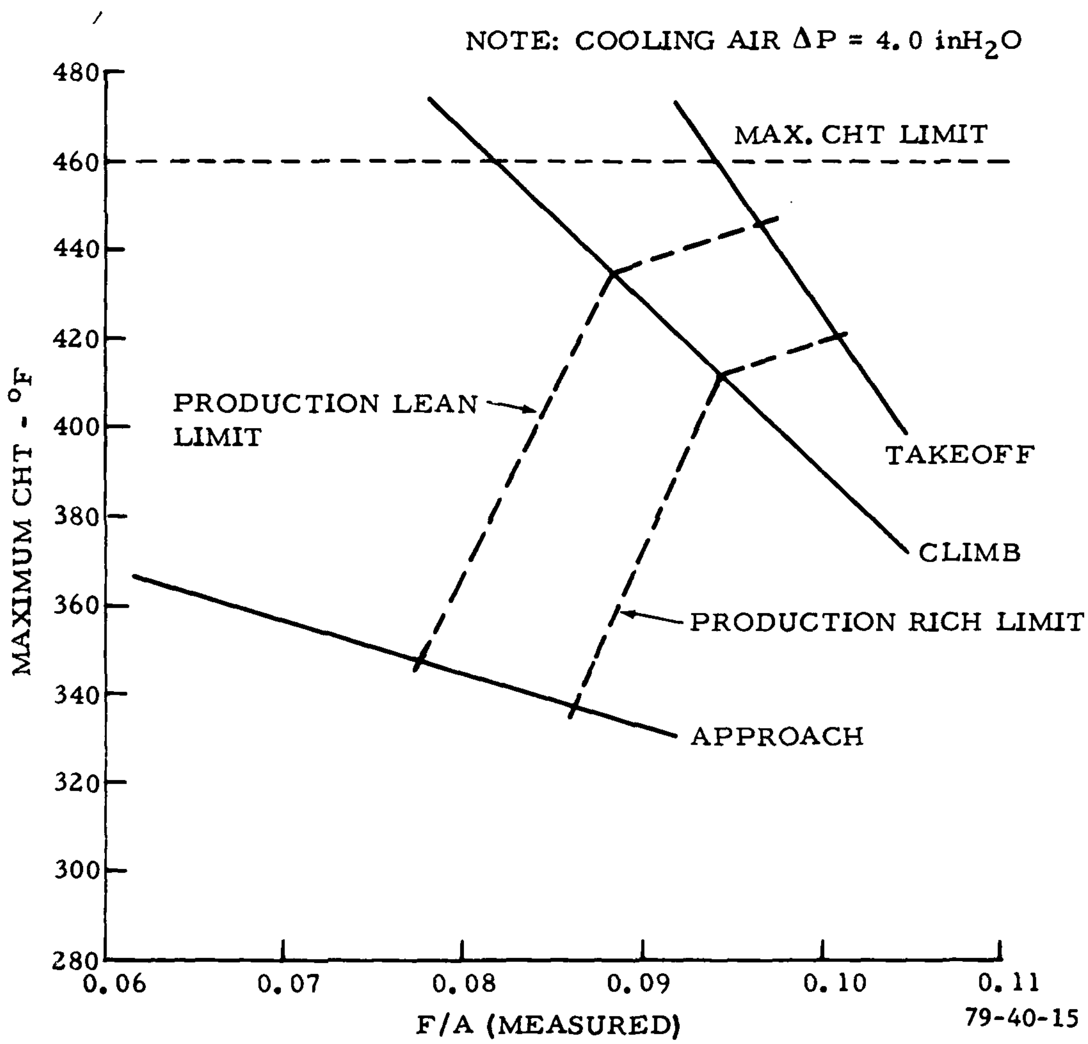

FIGURE 14. SEA LEVEL STANDARD-DAY MAXIMUM CYLINDER HEAD TEMPERATURES FOR DIFFERENT POWER MODE CONDITIONS AND VARYING FUEL-AIR RATIOS--TCM GTSIO-520--K ENGINE

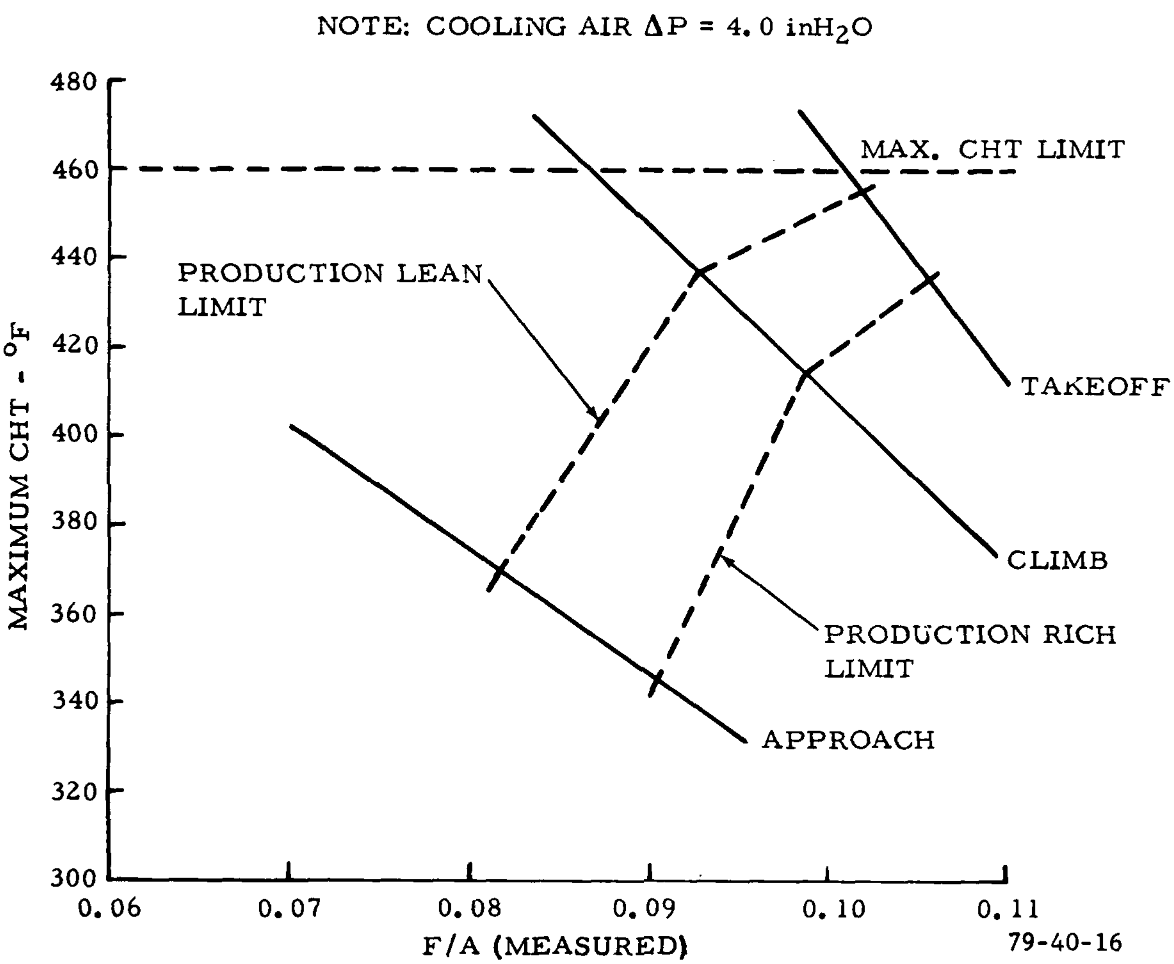

FIGURE 15. SEA LEVEL HOT-DAY (T_1=103° F) MAXIMUM CYLINDER HEAD TEMPERATURES FOR DIFFERENT POWER MODE CONDITIONS AND VARYING FUEL-AIR RATIOS--TCM GTSIO-520-K ENGINE

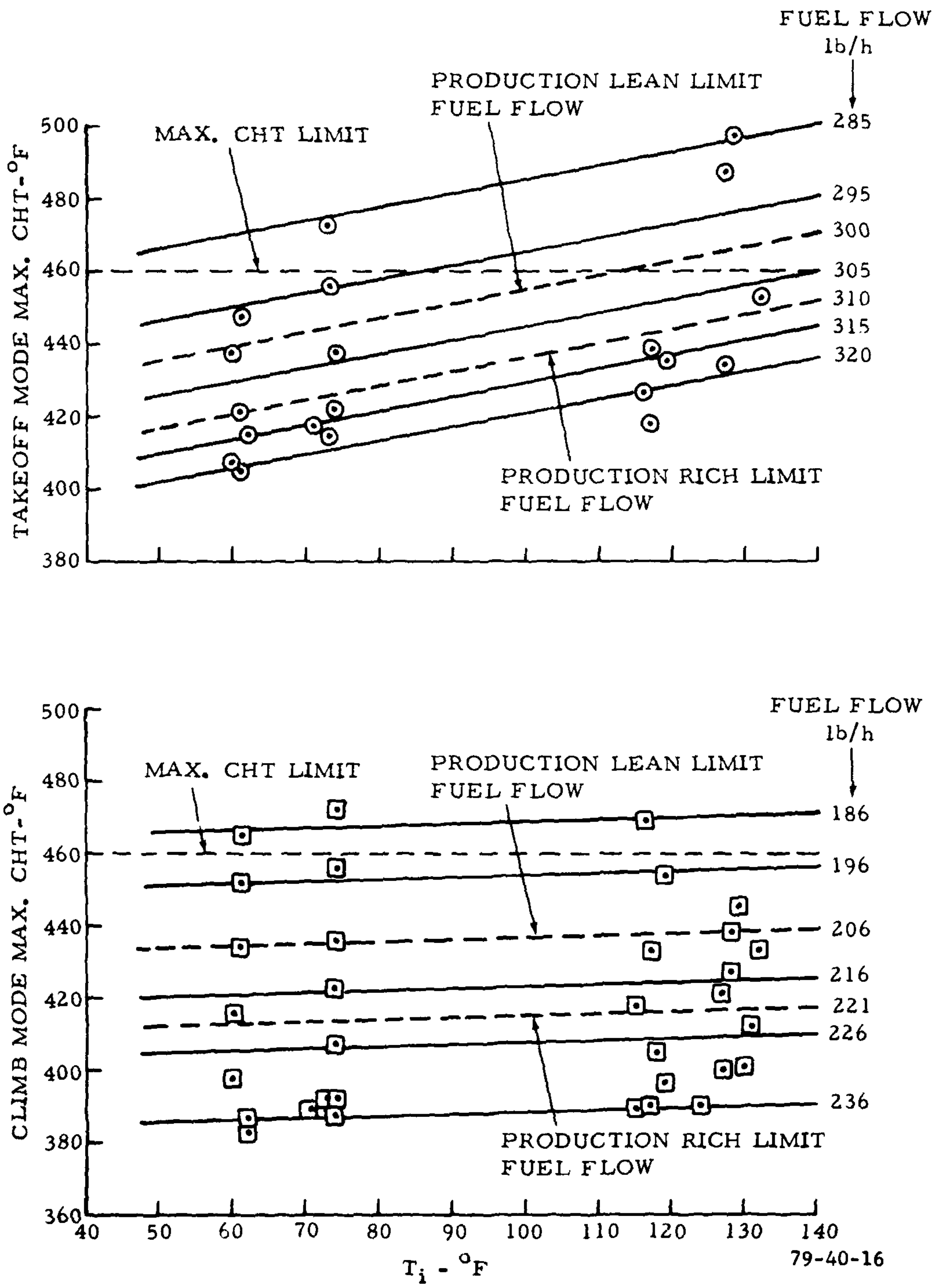

FIGURE 16. MAXIMUM CYLINDER HEAD TEMPERATURE CHARACTERISTICS FOR A TCM GTSIO-520-K ENGINE OPERATING ON A SEA LEVEL PROPELLER STAND WITH CONSTANT COOLING AIR FLOW (ΔP = 4.0 inH_2O)

SUMMARY OF RESULTS

EXHAUST EMISSIONS.

1. The GTSIO-520-K engine does not meet the proposed EPA carbon monoxide and unburned hydrocarbon standards for 1979/80 under sea level standard day conditions.

2. The GTSIO-520-K engine meets the EPA oxides of nitrogen standard for 1979/80.

3. The engine fuel metering device could be adjusted on the test stand to reduce the current CO exhaust emission level, but not to levels required by proposed EPA standards when operating under the LTO cycle requirements.

4. The engine could be adjusted on the test stand to reduce the unburned hydrocarbon exhaust emission level below the proposed EPA standard.

MAXIMUM CYLINDER HEAD TEMPERATURES.

1. Adjusting the fuel metering device in the takeoff and climb modes to constant best power operation results in an increase in maximum CHT, which will exceed the engine specification limit on the test stand if cooling air ΔP is limited to 4.0 inH_2O or less.

2. No critical maximum CHT's result from leaning-out the approach and taxi modes.

CRITICAL LANDING AND TAKEOFF CYCLE.

1. The most critical LTO cycle is the cycle defined in this report as maximum five-mode LTO cycle (table 4). Engine operation in accordance with the maximum five-mode LTO cycle in a sea level propeller test stand could not be adjusted to meet the proposed EPA CO-emission standard for 1979/80 without exceeding engine maximum CHT limits.

2. Engine operation in accordance with the minimum five-mode LTO cycle (table 5) could be adjusted to significantly improve the engine's emission levels.

CONCLUSIONS

The following conclusions are based on the testing accomplished with the TCM GTSIO-520-K engine.

1. The single use of simple fuel management adjustments (altering of fuel schedule) do not allow safe reduction of exhaust emissions of the test engine, the TCM GTSIO-520-K. In conjunction with other data, references 12, 13, 14, 15, and 16, this appears to be a valid general conclusion for typical light-aircraft piston engines.

2. The test data indicate that fuel management adjustments must be combined with engine/nacelle cooling modifications before safe and optimum low-emission aircraft/engine combinations can be achieved.

3. The EPA CO limit of 0.042 lb/cycle/rated BHP is not achievable when take-off and climb requirements are impacted by aircraft heavy gross weight and the need to pay close attention to CHT limitations.

4. Based on an assessment of the maximum five-mode LTO cycle (table 4) test data, it is concluded that the following standard changes should be made to the proposed EPA emission standards:

Proposed EPA Std. For 1979/80 (lb/cycle/rated BHP)	Proposed Change to the 1979/80 Std. (lb/cycle/rated BHP)
CO Standard 0.042	0.075
HC Standard 0.0019	0.0025
NO_x Standard 0.0015	0.0015

5. To avoid CHT problems in the takeoff mode (100-percent power), it is advisable not to adjust the fuel metering device. Engine operation in this mode should continue to be accomplished within current production rich/lean limits.

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APPENDIX A

FUEL SAMPLE ANALYSIS

COMBUSTIBLE ELEMENTS IN FUELS (AVIATION FUEL).

1. Carbon and hydrogen are the predominant combustible elements in fuels (aviation type), with small amounts of sulphur as the only other fuel element.

2. Liquid fuels are mixtures of complex hydrocarbons.

3. For combustion calculations, gasoline or fuel oil can be assumed to have the average molecular formula C_8H_{17}.

Note: The Exxon data presented in table A-1 may be found in reference 7.

TABLE A-1. TYPICAL SPECIFICATIONS FOR AVIATION FUELS

Item	D910-76 Grade 100/130	Exxon Aviation Gas 100/130	D910-70 Grade 115/145	Exxon Aviation Gas 115/145
Freezing Point, °F	-72 Max.	Below -76	-76 Max.	Below -76
Reid Vapor Press., PSI	7.0 Max.	6.8	7.0 Max.	6.8
Sulfur, % by Weight	0.05 Max.	0.02	0.05 Max.	0.02
Lower Heating Value, BTU/lb	18,720 Min.		18,800 Min.	
Heat of Comb. (NET). BTU/lb		18,960		19,050
Distillation, %Evaporated				
At 167° F (Max.)	10	22	10	21
At 167° F (Min.)	40		40	
At 221° F (Max.)	50	76	50	62
At 275° F (Max.)	90	97	90	96
Distillation End Point	338° F Max.		338° F Max.	
Final Boiling Point °F		319		322
Tel Content, ML/U.S. Gal.	4.0 Max.	3.9	4.6 Max.	4.5
Color	Green	Green	Purple	Purple

4. NAFEC used 100/130 (octane rated) aviation gasoline for the piston engine emission tests. The following analysis of a typical fuel sample (table A-2) made at the U.S. Naval Air Propulsion Test Center (NAPTC), Trenton, N.J. (reference 8).

TABLE A-2. ANALYSIS OF NAFEC FUEL SAMPLE, 100/130 FUEL

Item	NAFEC Sample 100/130	Grade 100/130 (MIL-G-5572E) Spec Limits Min.		Max.
Freezing Point, °F	Below -76° F			-76
Reid Vapor Press., PSI	6.12	5.5		7.0
Sulfur % By Weight	0.024			0.05
Lower Heating Value BTU/lb		18,700		
Heat of Comb. (NET) BTU/lb	18,900			
Distillation, % Evaporated			Distillation % Evaporation	
At 158° F	10			
At 167° F (Min.)		167° F	10	
At 167° F (Max.)			40	167° F
At 210° F	40			
At 220° F	50			
At 221° F		221° F	50	
At 242° F	90			
At 275° F		275° F	90	
Distillation End Point	313° F			338° F
Specific Gravity @60° F	0.7071	Report		Report
API Gravity @60° F	68.6		No Limit	
Tel Content, ML/U.S. Gal.	1.84			4.60

Computation for the fuel hydrogen-carbon ratio is based on the fuel net heating value, h_f, equal to 18,900 BTU/lb and figure A-1.

$C/H = 5.6$

$C = 12.011$

$C_8 = 8 \times 12.011 = 96.088$

$H_y = (96.088) \div 5.6 = 17.159$

$H = 1.008$

$Y = (17.159) \div 1.008 = 17.022$ Use $Y = 17$

APPENDIX B

COMPOSITION OF AIR (GENERAL PROPERTIES)

1. Dry air is a mixture of gases that has a representative volumetric analysis in percentages as follows:

Oxygen (O_2)—20.99%
Nitrogen (N_2)—78.03%
Argon (A)—0.94% (Also includes traces of the rare gases neon, helium, and krypton)
Carbon Dioxide (CO_2)—0.03%
Hydrogen (H_2)—0.01%

2. For most calculations it is sufficiently accurate to consider dry air as consisting of:

O_2 = 21.0%
N_2 = 79.0% (including all other inert gases)

3. The moisture or humidity in atmospheric air varies over wide limits, depending on meteorological conditions, its presence in most cases simply implies an additional amount of essentially inert material.

Note: Information given in items 1, 2, and 3 is recommended for computation purposes (reference 3, 4, 9, and 10).

TABLE B-1. MASS ANALYSIS OF PURE DRY AIR

Gas	Volumetric Analysis %	Mole Fraction	Molecular Weight	Relative Weight
O_2	20.99	0.2099	32.00	6.717
N_2	78.03	0.7803	28.016	21.861
A	0.94	0.0094	39.944	0.376
CO_2	0.03	0.0003	44.003	0.013
Inert Gases	0.01	0.0001	48.0	0.002
	100.00	1.000		28.969 = M for air

4. The molecular weight of the apparent nitrogen can be similarly determined by dividing the total mass of the inert gases by the total number of moles of these components:

$$M_{\substack{\text{Apparent}\\ \text{Nitrogen}}} = \frac{2225}{79.01} = 28.161$$

5. This appendix advocates the term nitrogen as referring to the entire group of inert gases in the atmosphere and therefore the molecular weight of 28.161 will be the correct value (rather than the value 28.016 for pure nitrogen).

6. In combustion processes the active constituent is oxygen (O_2), and the apparent nitrogen can be considered to be inert. Then for every mole of oxygen supplied, 3.764 moles of apparent nitrogen accompany or dilute the oxygen in the reaction:

$$\frac{79.01}{20.99} = 3.764 \frac{\text{Moles Apparent Nitrogen}}{\text{Mole Oxygen}}$$

7. The information given in items 4, 5, and 6 is recommended for computational purposes in reference 4. Therefore, one mole of air (dry), which is composed of one mole of oxygen (O_2) and 3.764 moles of nitrogen (N_2), has a total weight of 137.998 pounds.

$$(O_2 + 3.764\ N_2) = 137.998$$

This gives the molecular weight of air = 28.97.

APPENDIX C

NAFEC TEST DATA AND WORKING PLOTS FOR ANALYSIS AND EVALUATION TELEDYNE CONTINENTAL MOTORS (TCM) GTSIO-520-K ENGINE

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

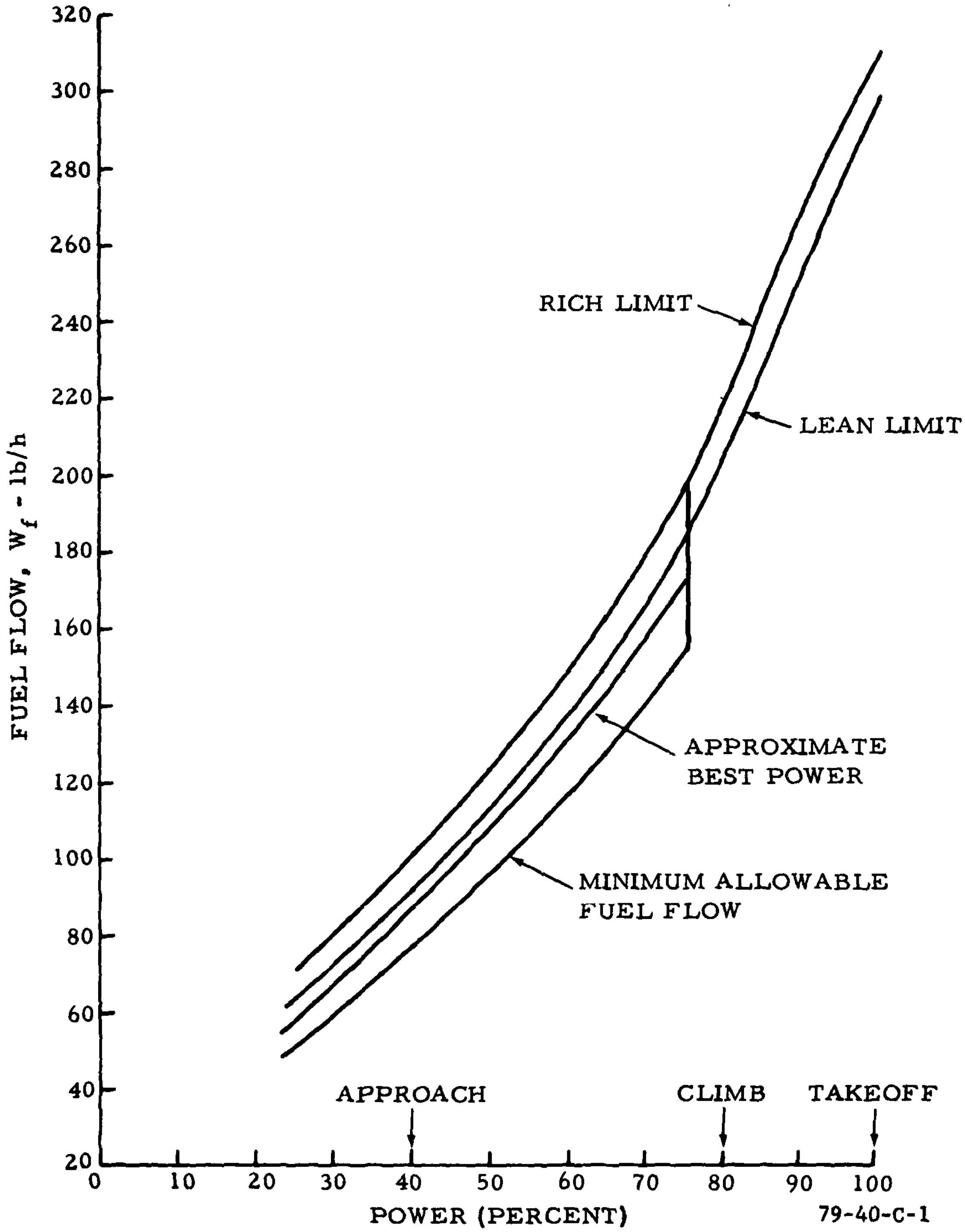

FIGURE C-1. SEA LEVEL PERFORMANCE--RECOMMENDED FUEL FLOW VERSUS PERCENT POWER--TCM GTSIO-520-K ENGINE (reference 17)

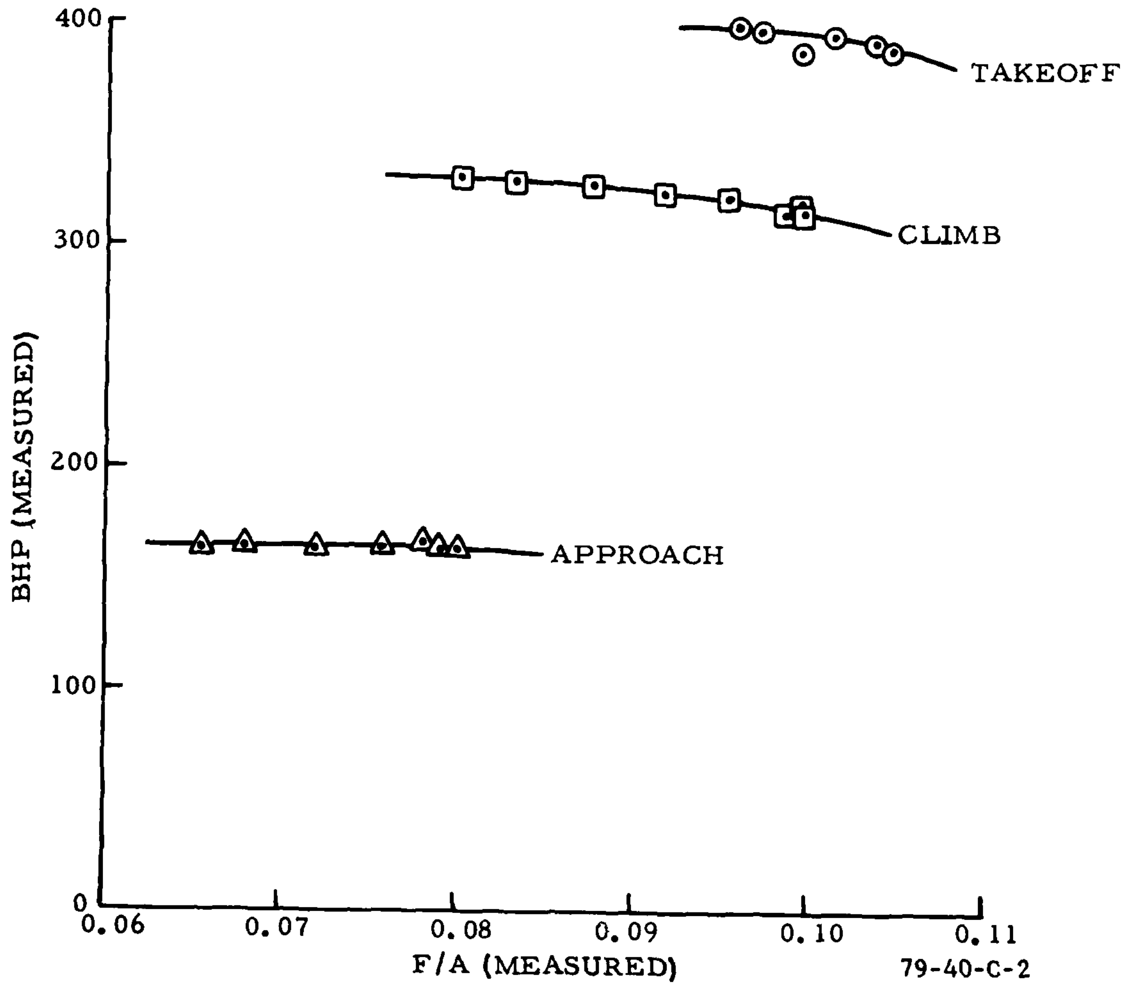

FIGURE C-2. MEASURED PERFORMANCE--TCM GTSIO-520-K ENGINE -- TAKEOFF, CLIMB, AND APPROACH MODES--NOMINAL SEA LEVEL AIR DENSITY 0.0762 lb/ft^3

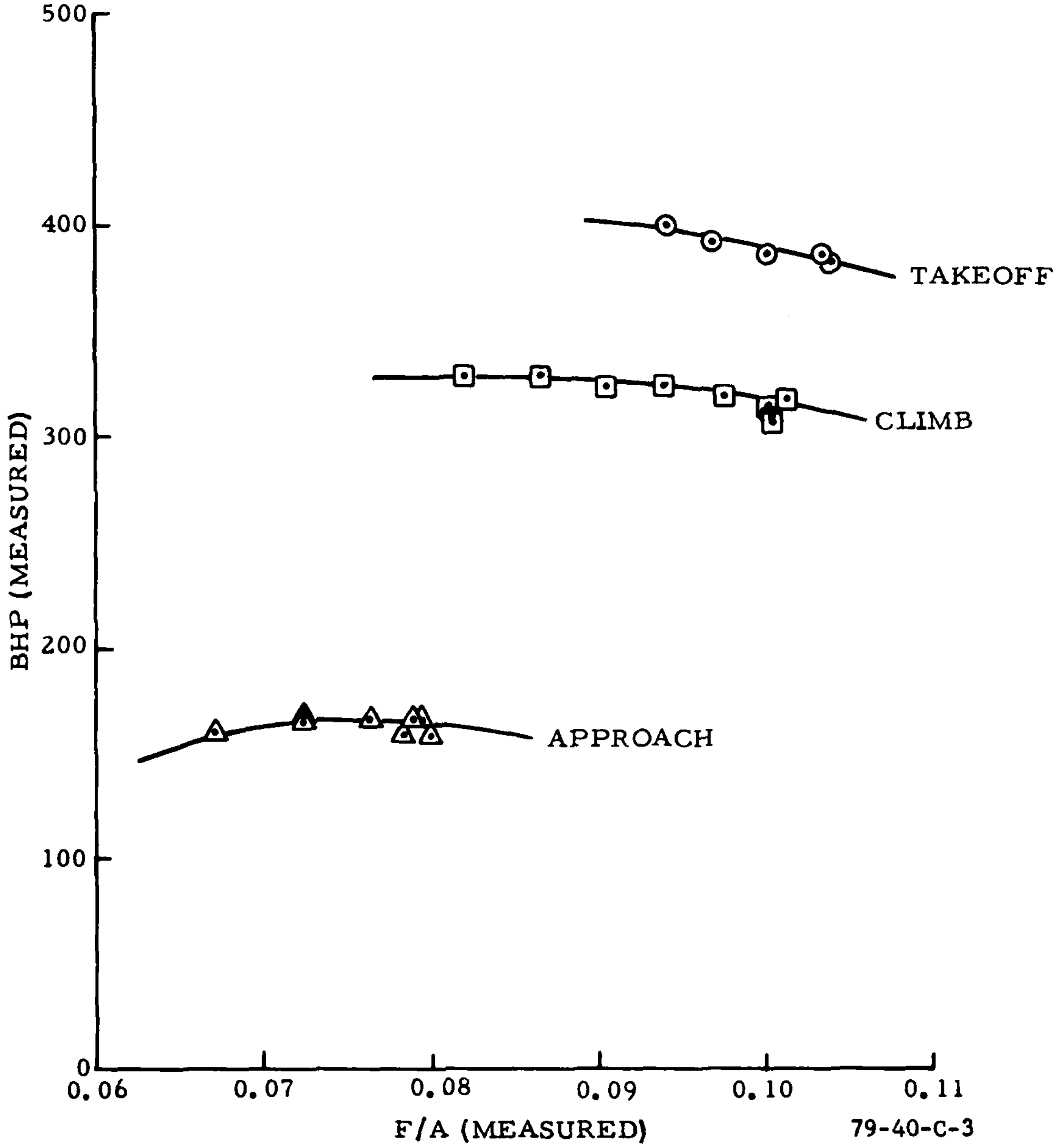

FIGURE C-3. MEASURED PERFORMANCE--TCM GTSIO-520-K ENGINE--TAKEOFF, CLIMB, AND APPROACH MODES--NOMINAL SEA LEVEL AIR DENSITY 0.0752 lb/ft^3

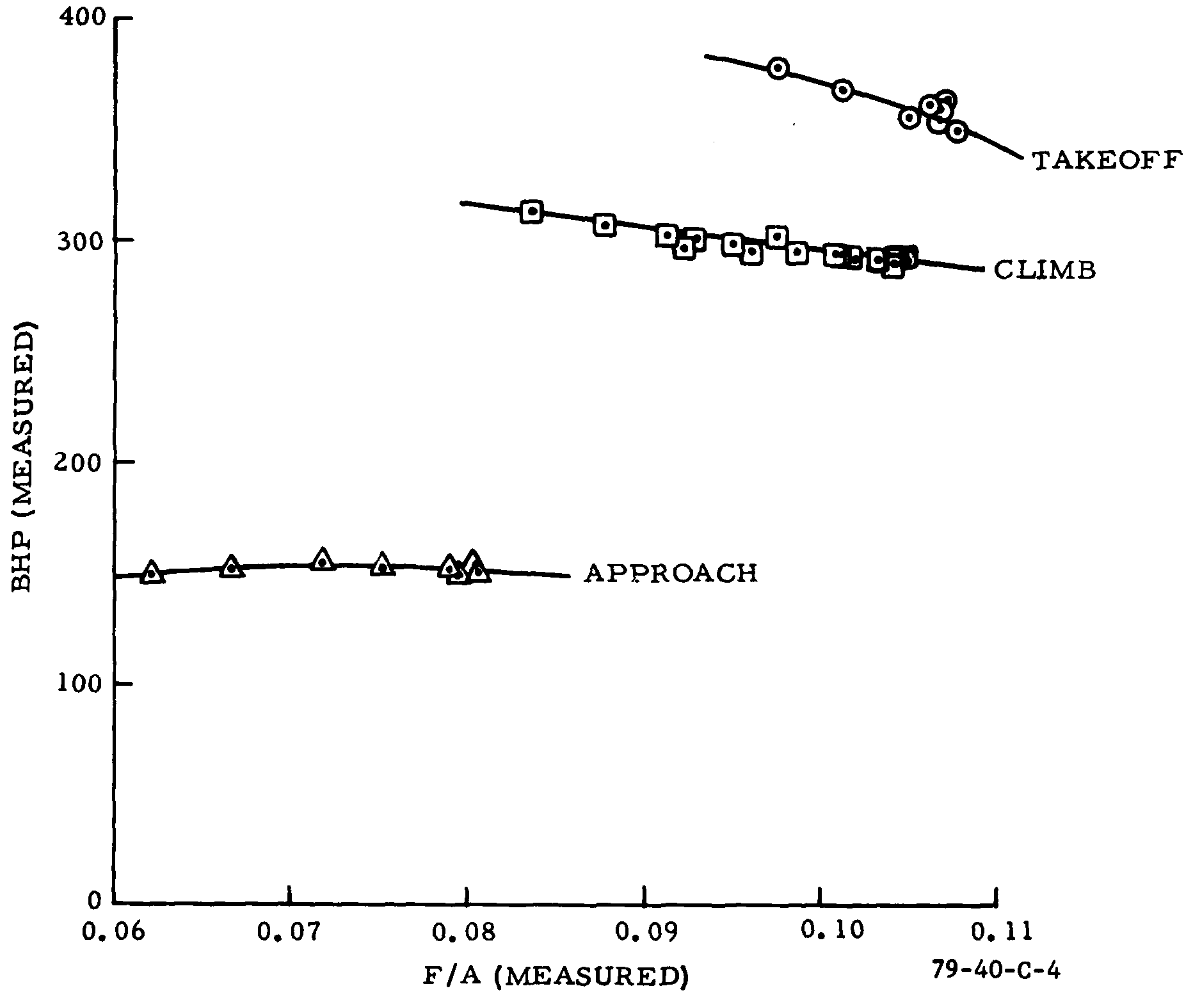

FIGURE C-4. MEASURED PERFORMANCE--TCM GTSIO-520-K ENGINE--TAKEOFF, CLIMB, AND APPROACH MODES--NOMINAL SEA LEVEL AIR DENSITY 0.0699 lb/ft^3

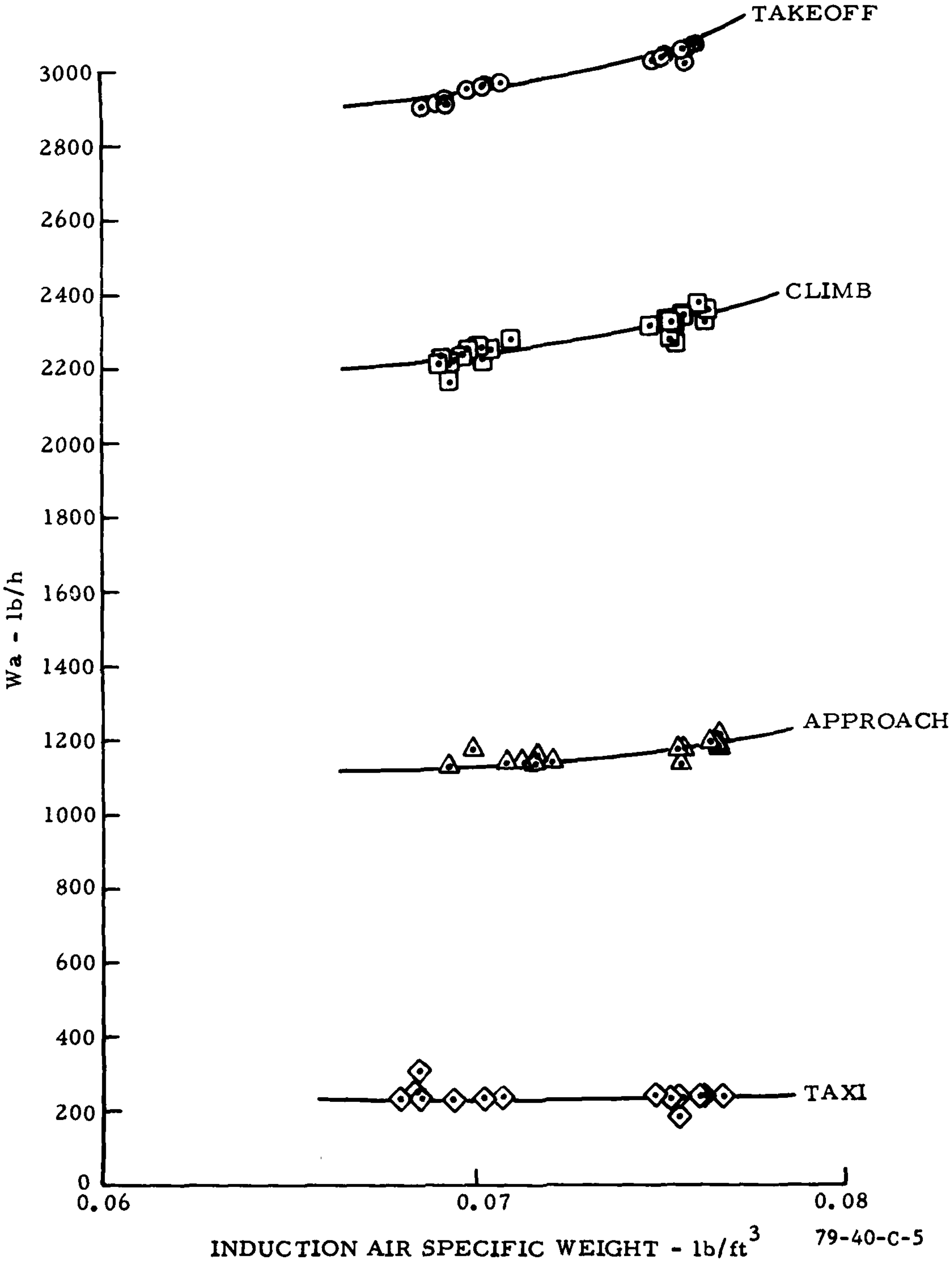

FIGURE C-5. AIRFLOW AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR A TCM GTSIO-520-K ENGINE--NOMINAL SEA LEVEL TEST DATA

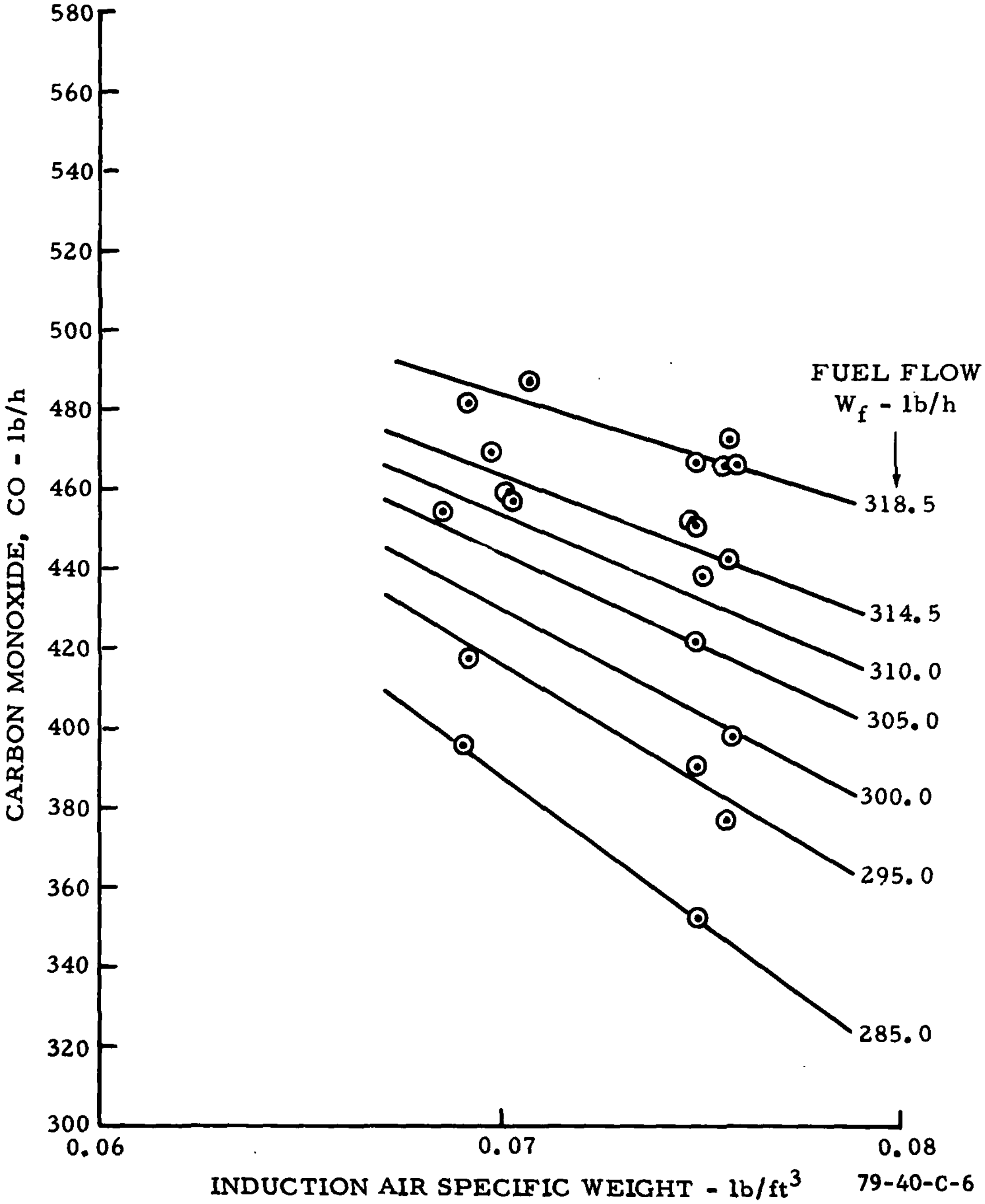

FIGURE C-6. EXHAUST CARBON MONOXIDE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL TAKEOFF CONSTANT FUEL FLOW SCHEDULES--TCM GTSIO-520-K ENGINE

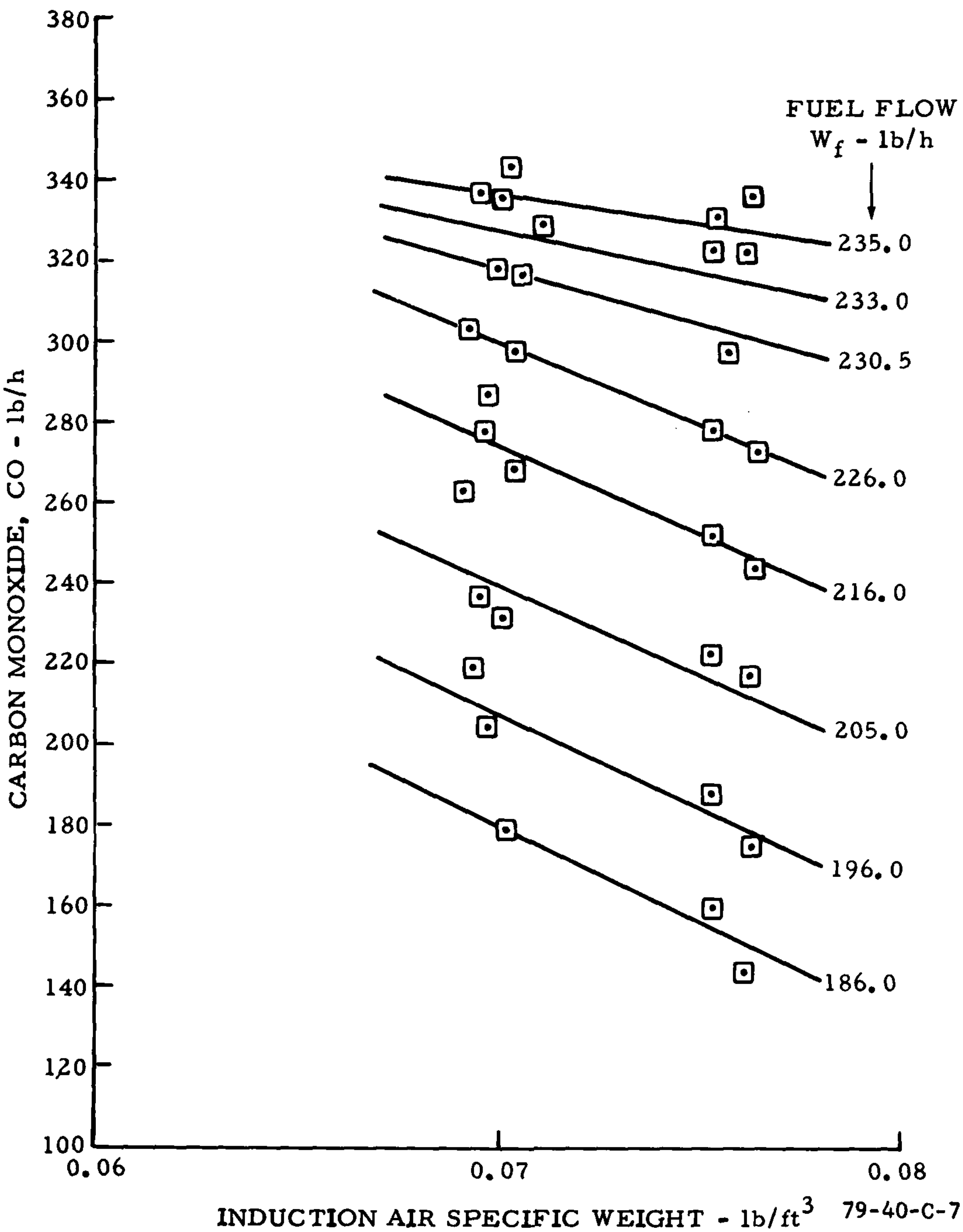

FIGURE C-7. EXHAUST CARBON MONOXIDE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL CLIMB MODE CONSTANT FUEL FLOW SCHEDULES--TCM GTSIO-520-K ENGINE

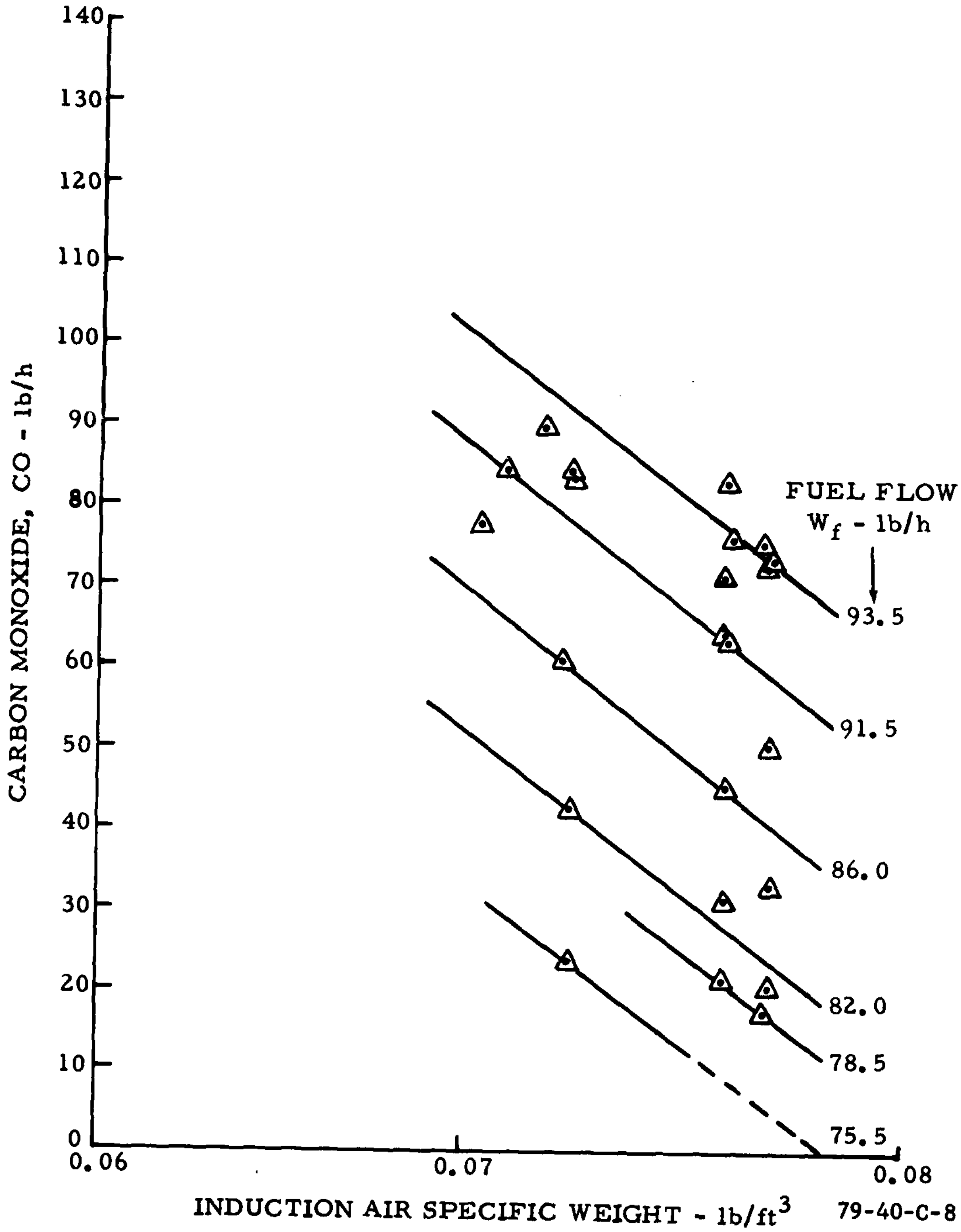

FIGURE C-8. EXHAUST CARBON MONOXIDE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL APPROACH MODE CONSTANT FUEL FLOW SCHEDULES--TCM GTSIO-520-K ENGINE

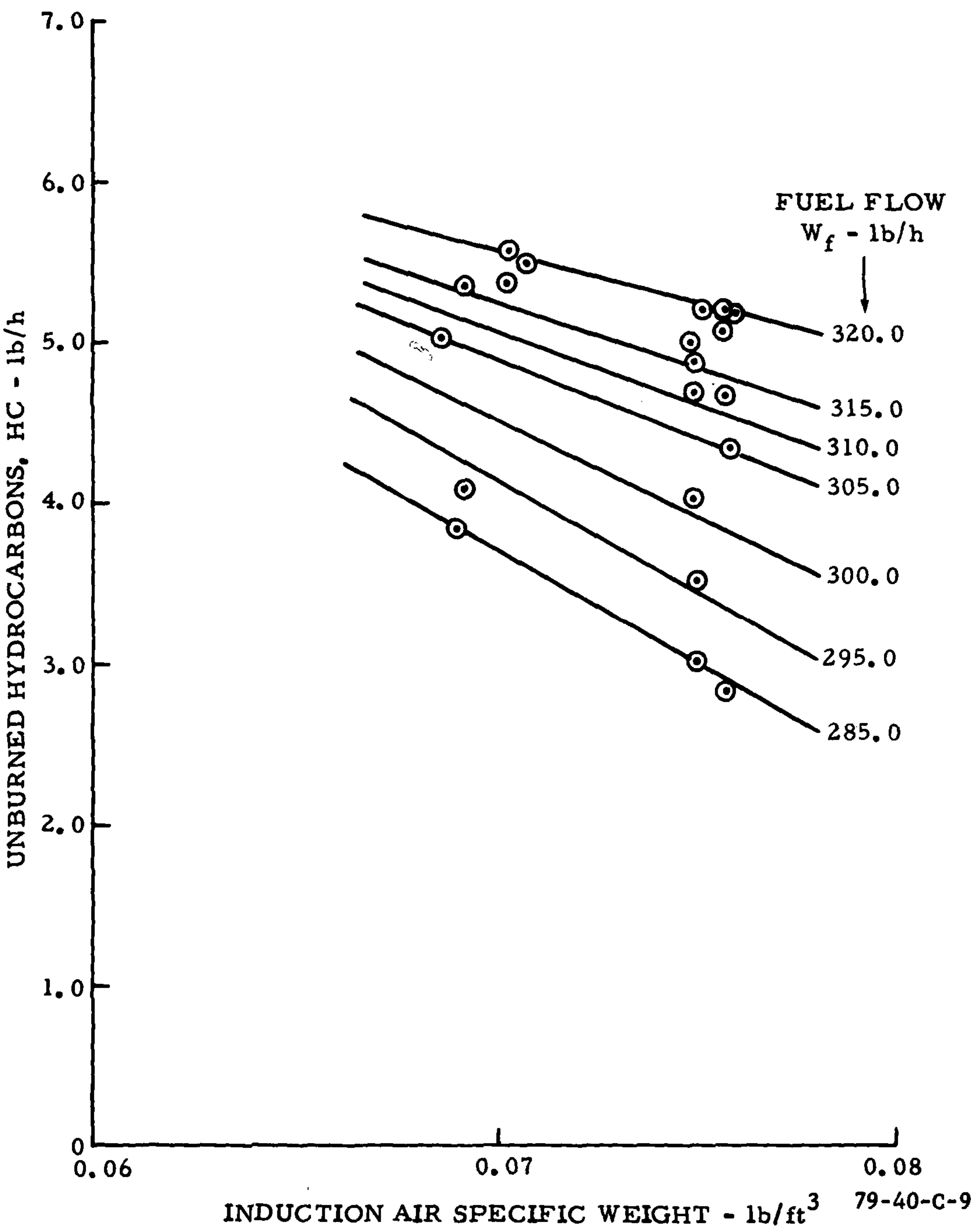

FIGURE C-9. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL TAKEOFF CONSTANT FUEL FLOW SCHEDULES--TCM GTSIO-520-K ENGINE

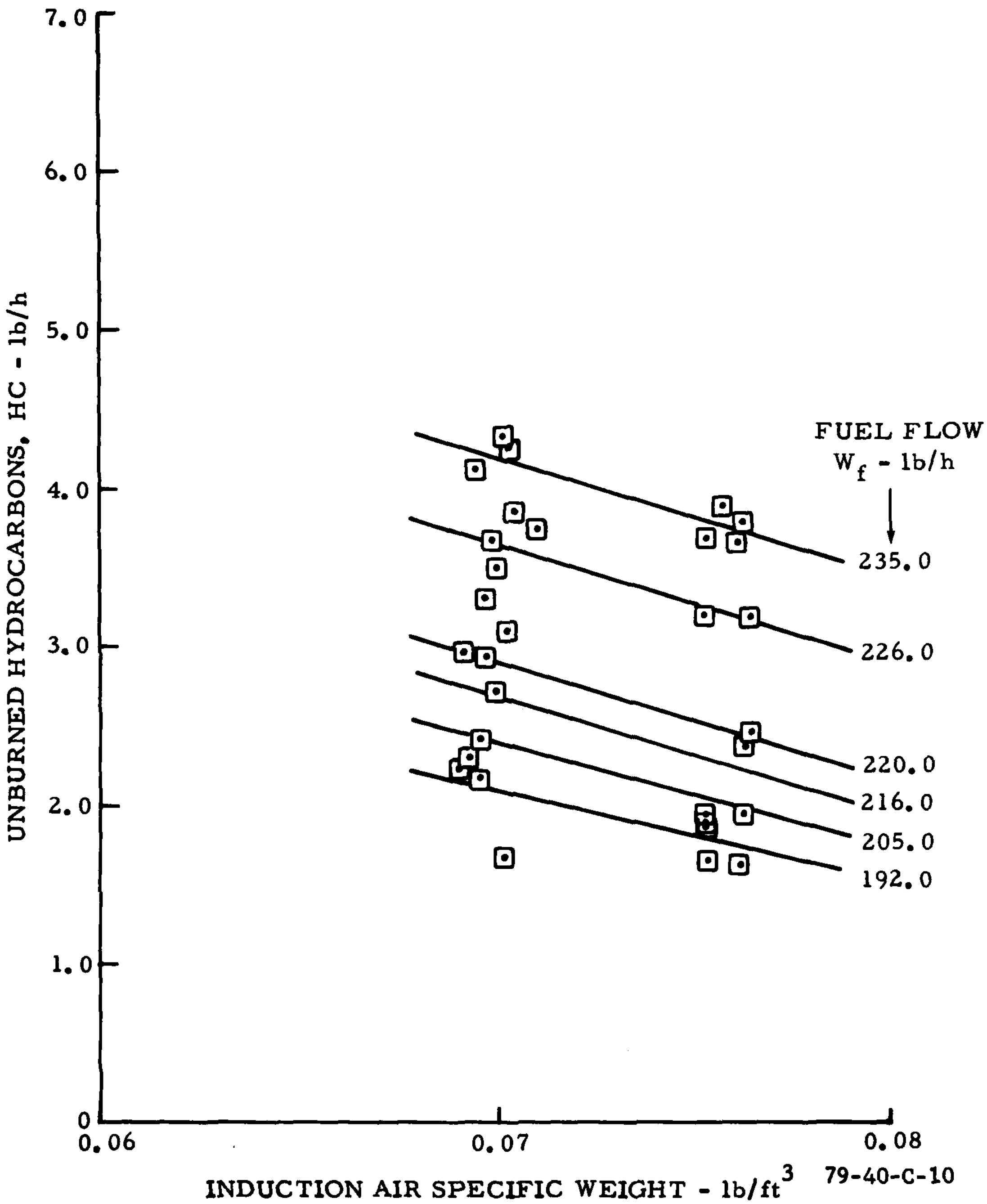

FIGURE C-10. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL CLIMB MODE CONSTANT FUEL FLOW SCHEDULES--TCM GTSIO-520-K ENGINE

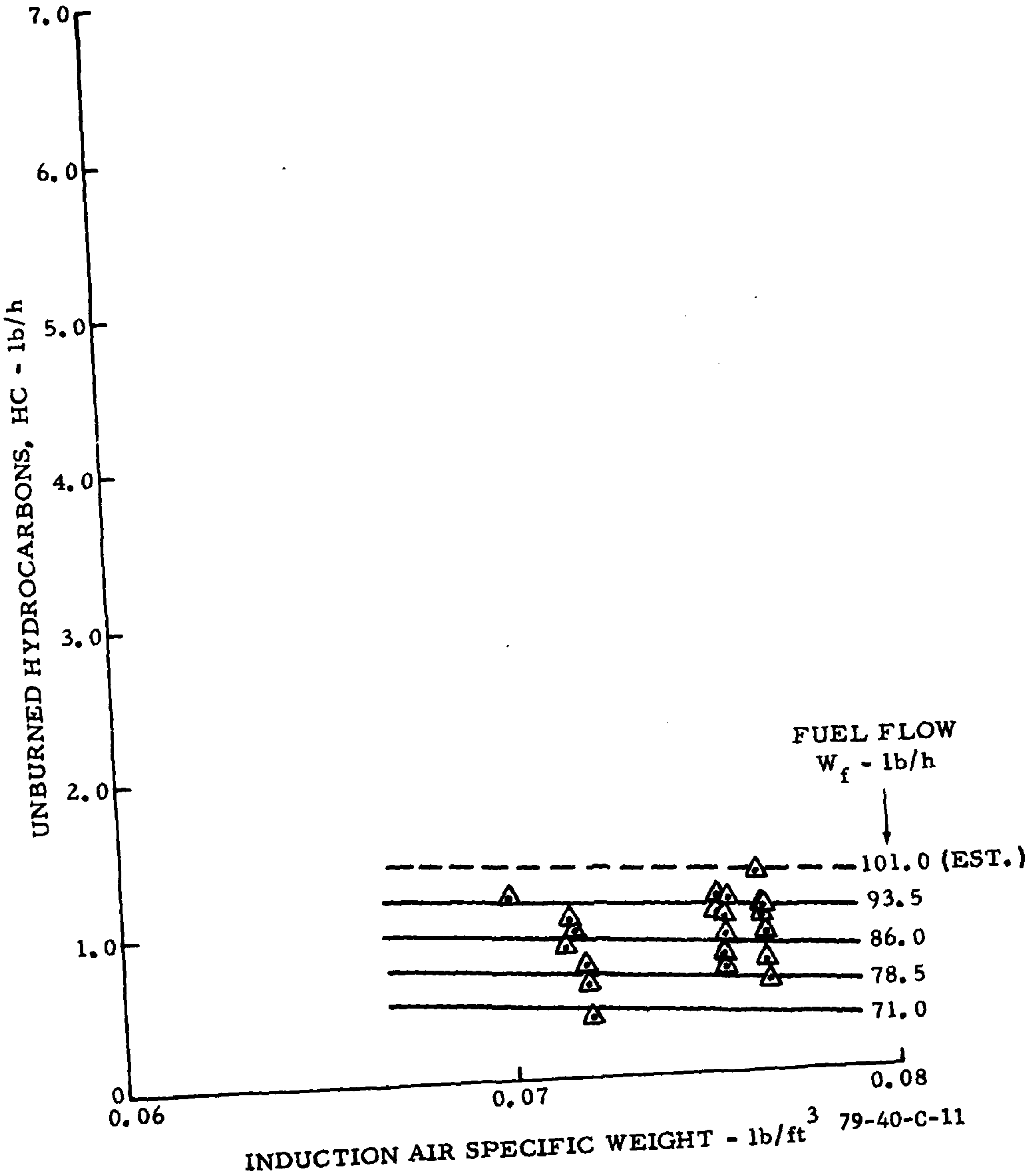

FIGURE C-11. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL APPROACH MODE CONSTANT FUEL FLOW SCHEDULES--TCM GTSIO-520-K ENGINE

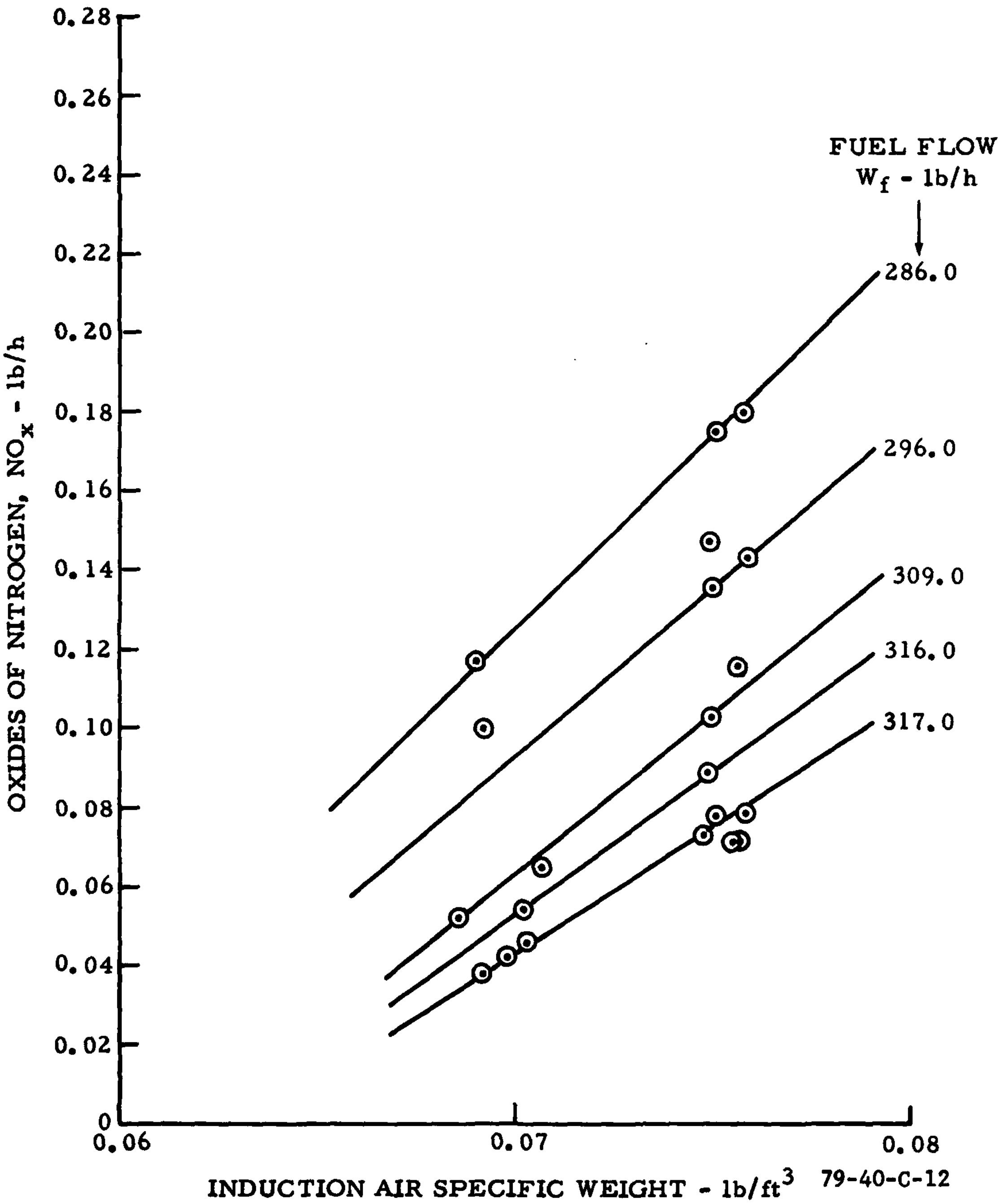

FIGURE C-12. OXIDES OF NITROGEN AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL TAKEOFF CONSTANT FUEL FLOW SCHEDULES--TCM GTSIO-520-K ENGINE

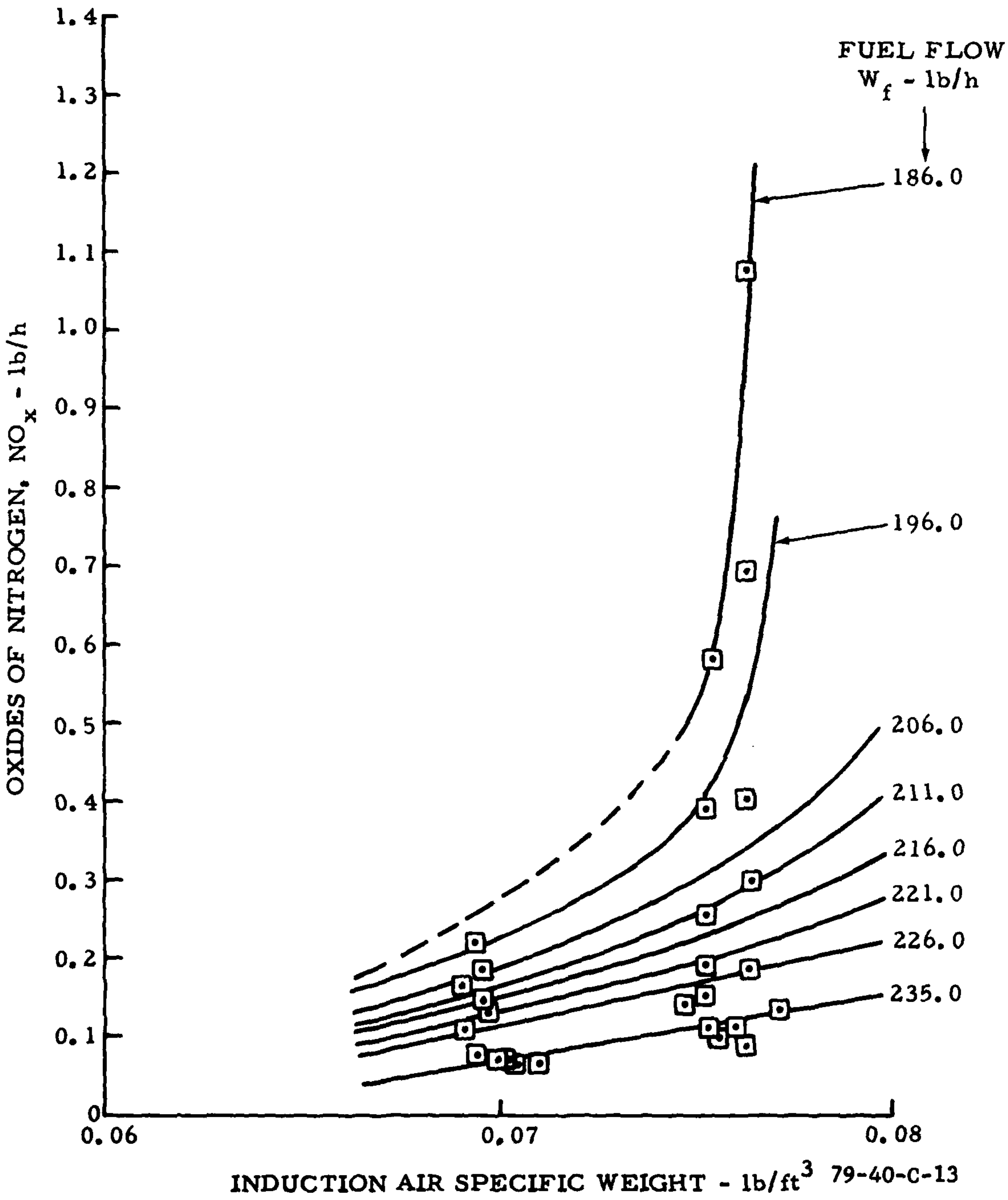

FIGURE C-13. OXIDES OF NITROGEN AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL CLIMB MODE CONSTANT FUEL FLOW SCHEDULES--TCM GTSIO-520-K ENGINE

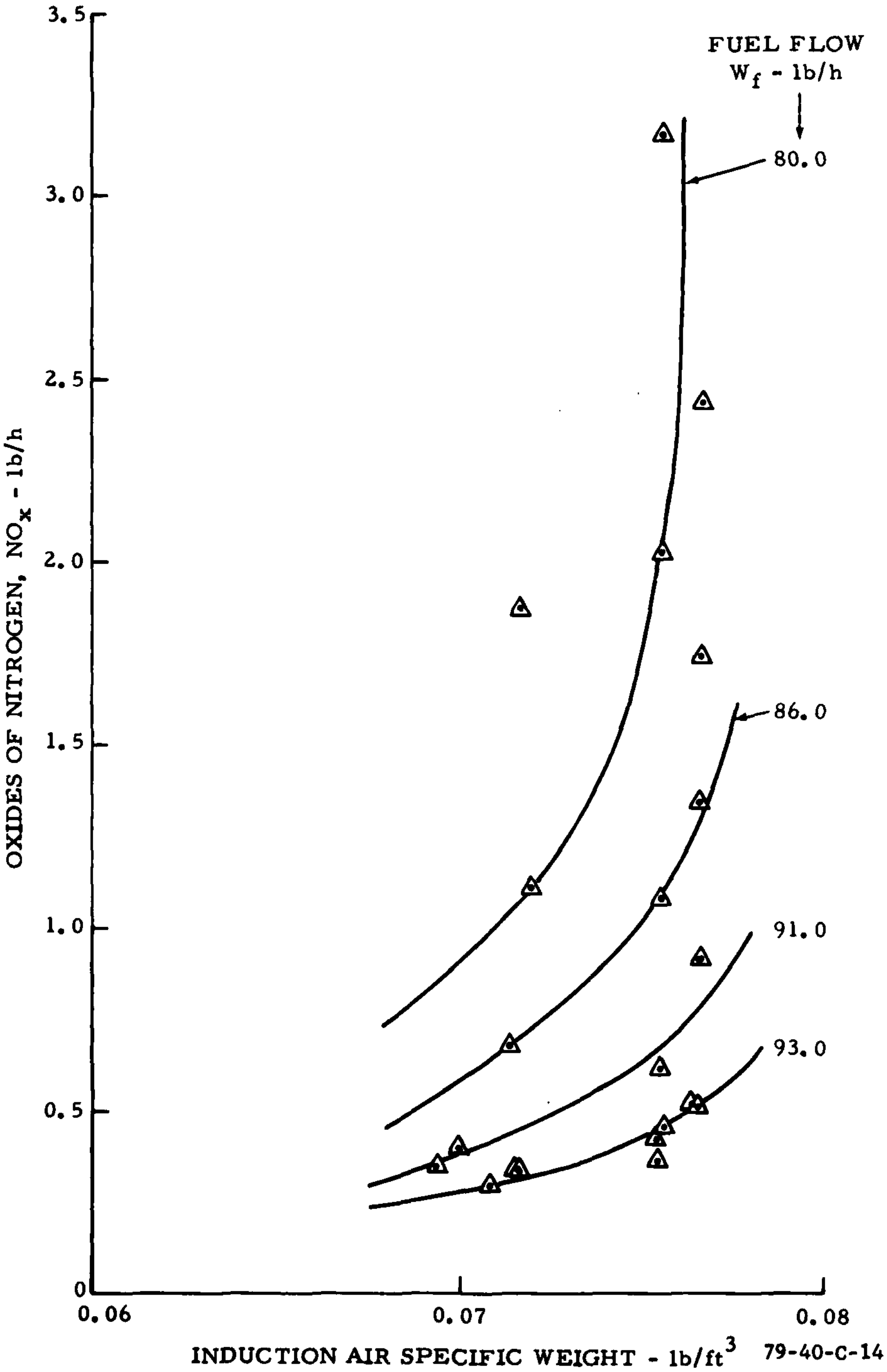

FIGURE C-14. OXIDES OF NITROGEN AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL APPROACH MODE CONSTANT FUEL FLOW SCHEDULES--TCM GTSIO-520-K ENGINE

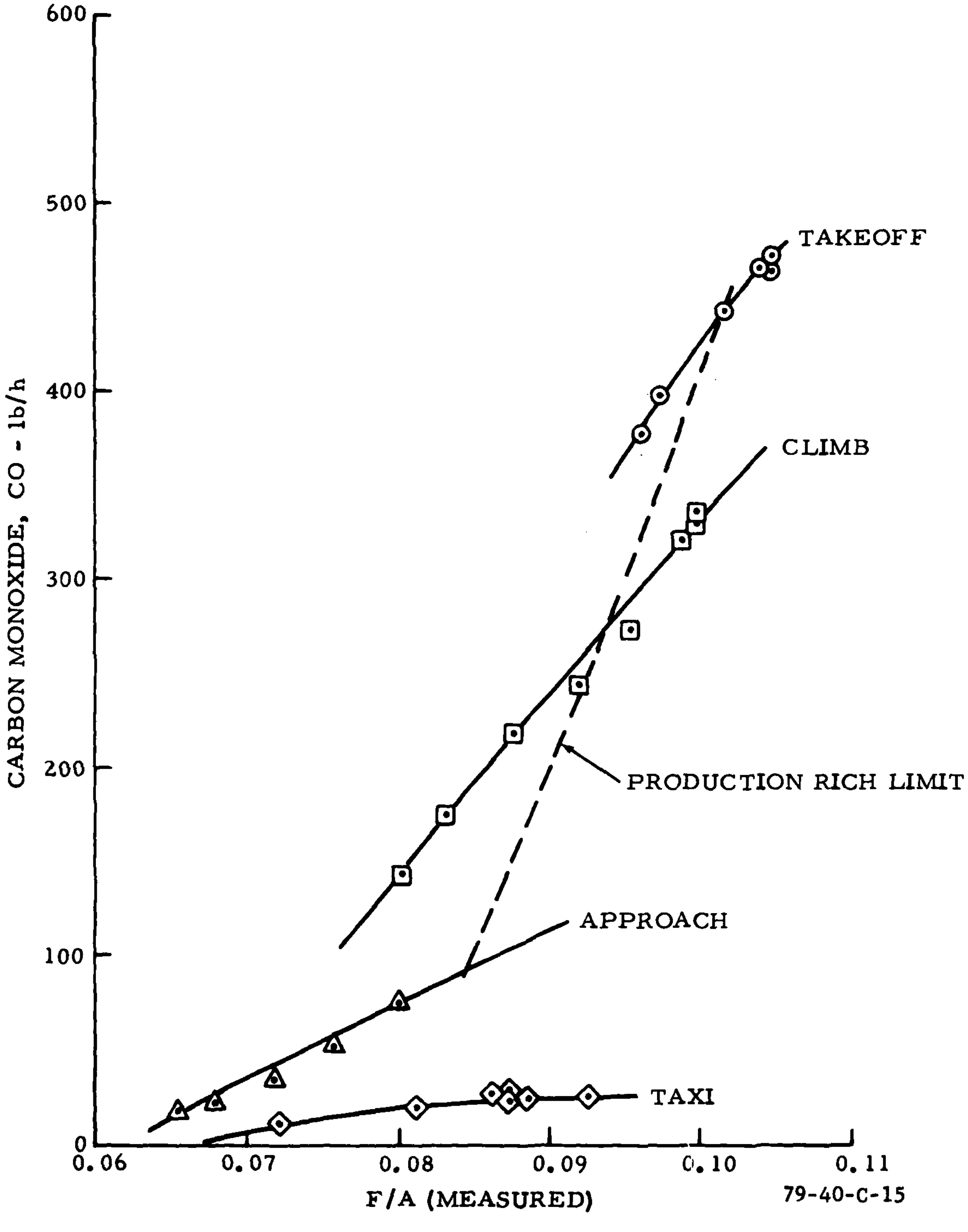

FIGURE C-15. SEA LEVEL STANDARD-DAY EMISSION CHARACTERISTICS FOR A TCM GTSIO-520-K ENGINE--CARBON MONOXIDE

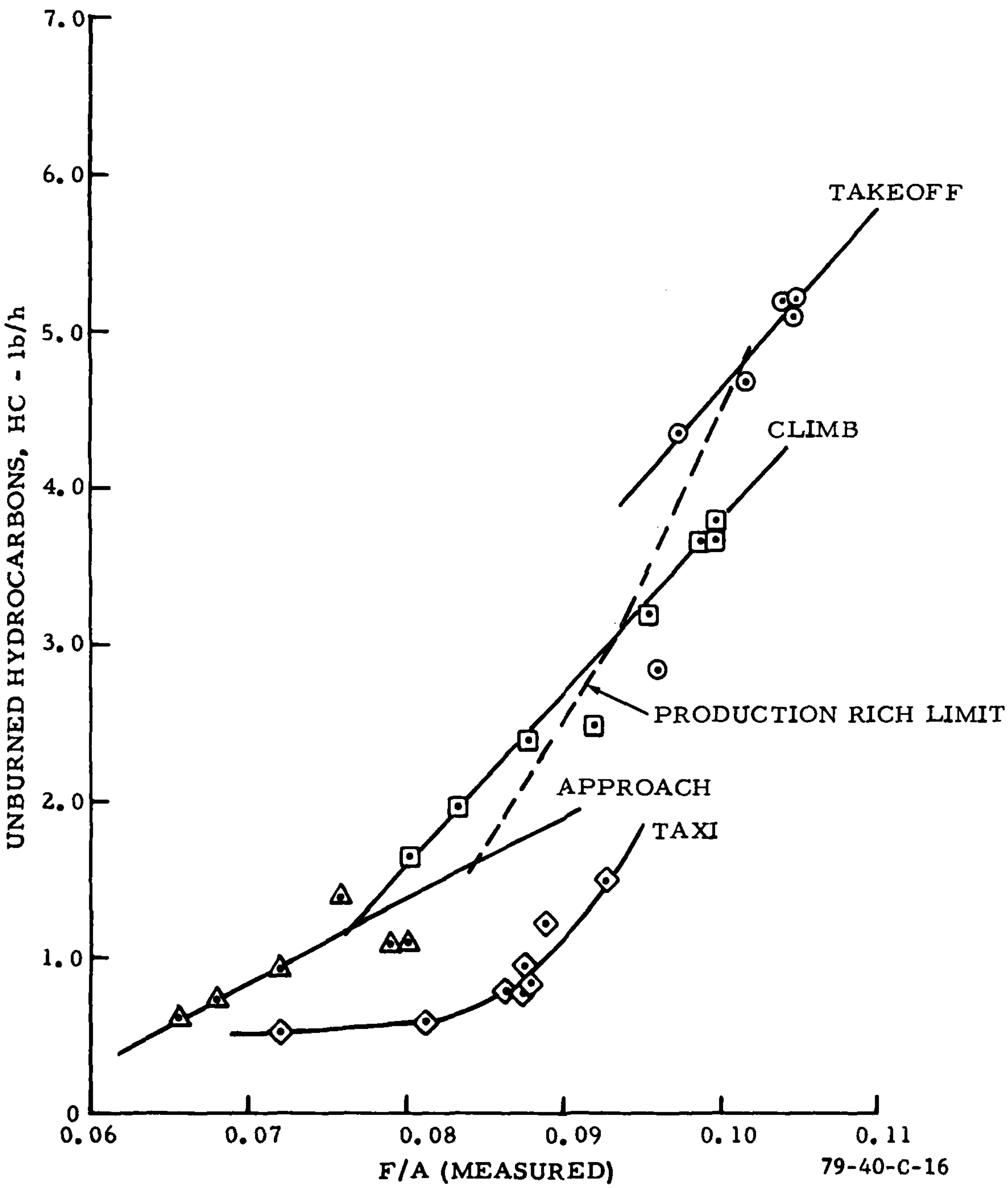

FIGURE C-16. SEA LEVEL STANDARD-DAY EMISSIONS CHARACTERISTICS FOR A TCM GTSIO-520-K ENGINE--UNBURNED HYDROCARBONS

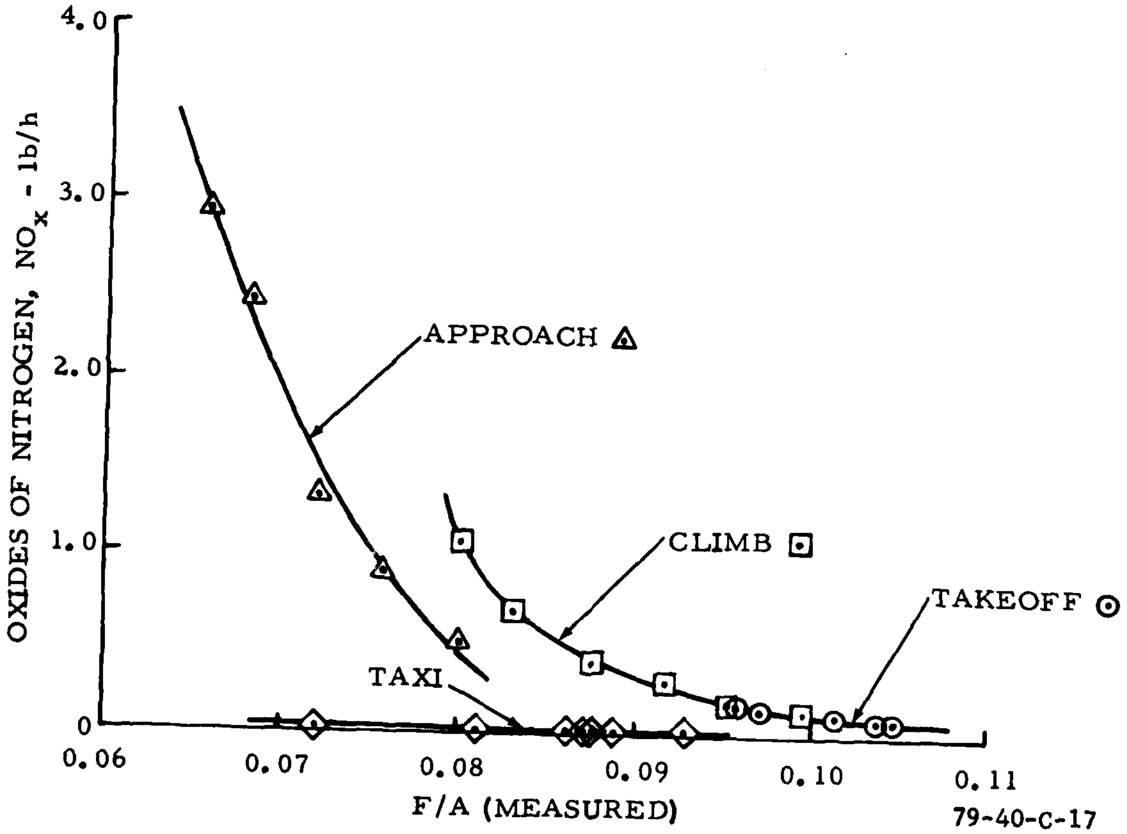

FIGURE C-17. SEA LEVEL STANDARD-DAY EMISSIONS CHARACTERISTICS FOR A TCM GTSIO-520-K ENGINE--OXIDES OF NITROGEN

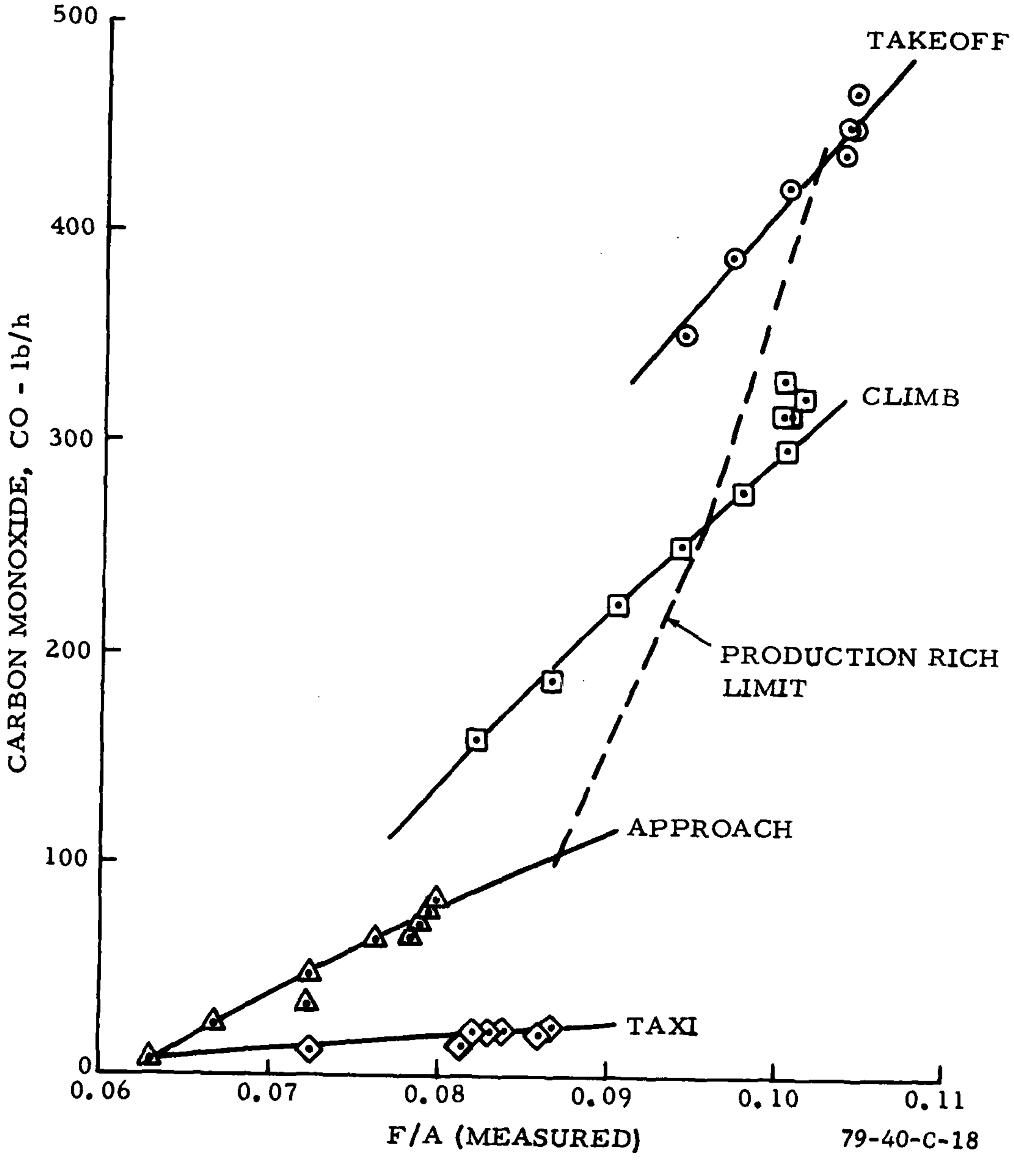

FIGURE C-18. SEA LEVEL WARM-DAY (T_i=75° F) EMISSIONS CHARACTERISTICS FOR A TCM GTSIO-520-K ENGINE--CARBON MONOXIDE

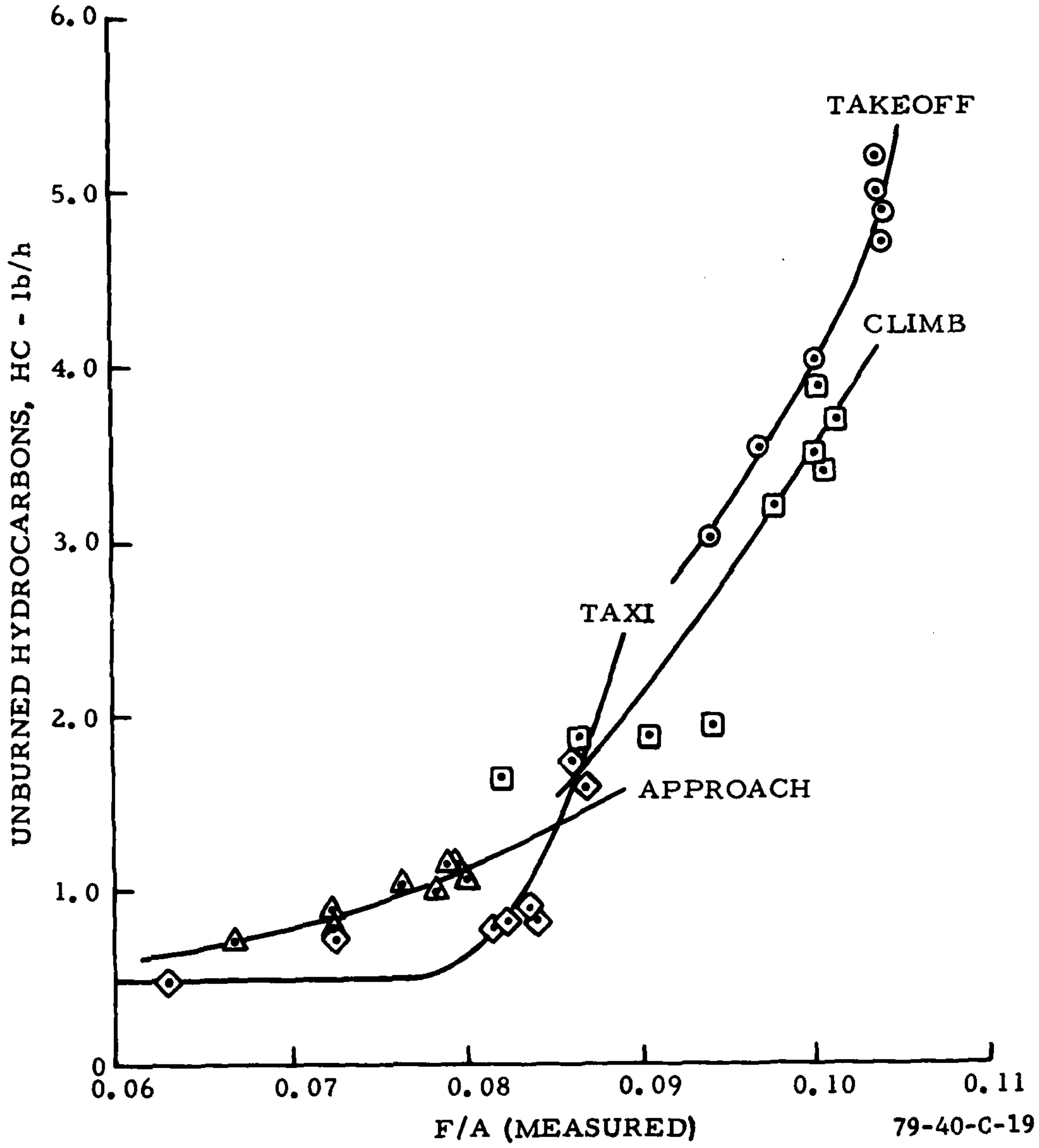

FIGURE C-19. SEA LEVEL WARM-DAY (T_1=75° F) EMISSIONS CHARACTERISTICS FOR A TCM GTSIO-520-K ENGINE--UNBURNED HYDROCARBONS

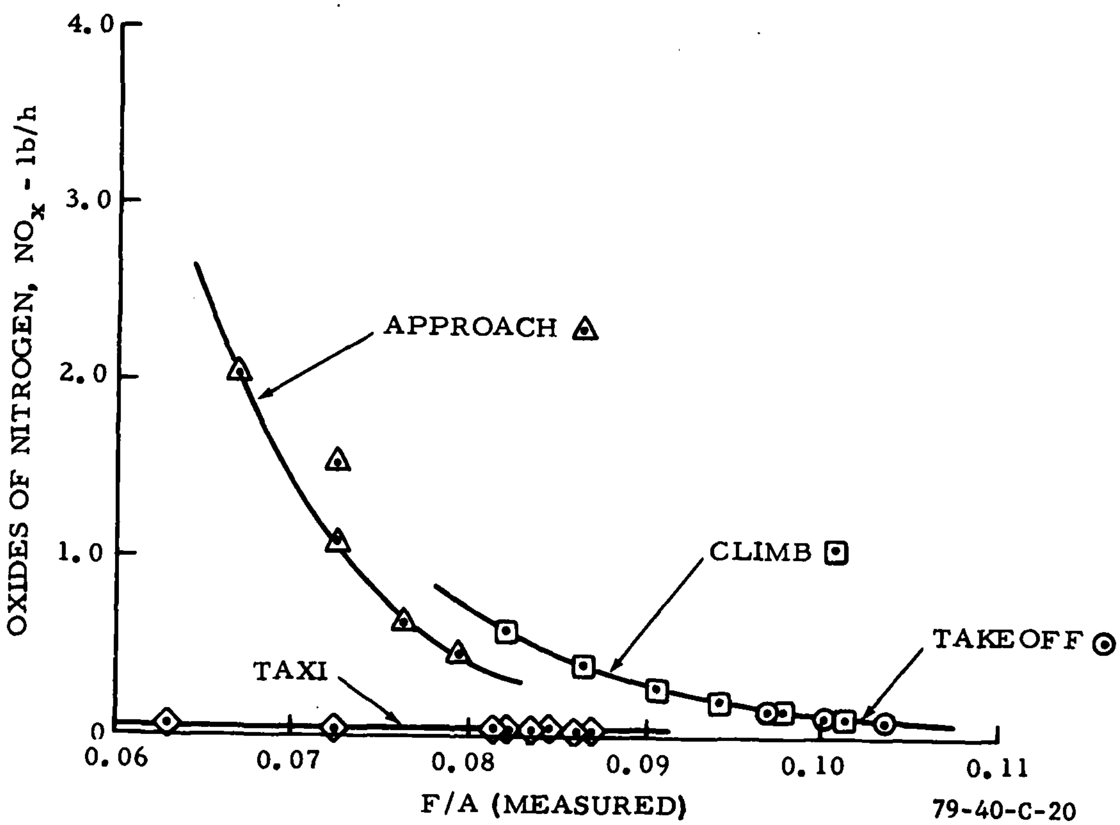

FIGURE C-20. SEA LEVEL WARM-DAY (T_i=75° F) EMISSIONS CHARACTERISTICS FOR A TCM GTSIO-520-K ENGINE--OXIDES OF NITROGEN

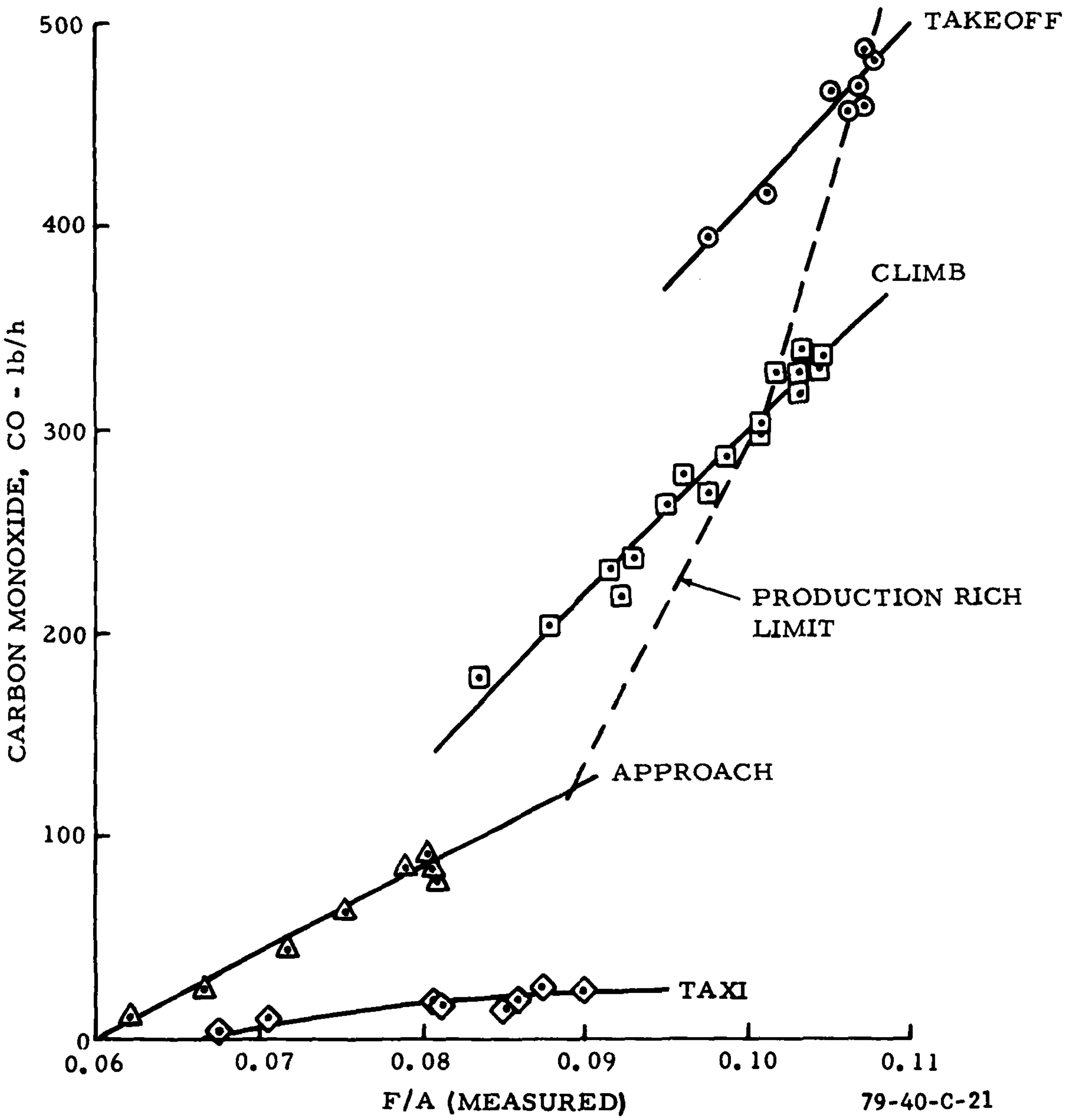

FIGURE C-21. SEA LEVEL HOT-DAY (T_1=120° F) EMISSIONS CHARACTERISTICS FOR A TCM GTSIO-520-K ENGINE--CARBON MONOXIDE

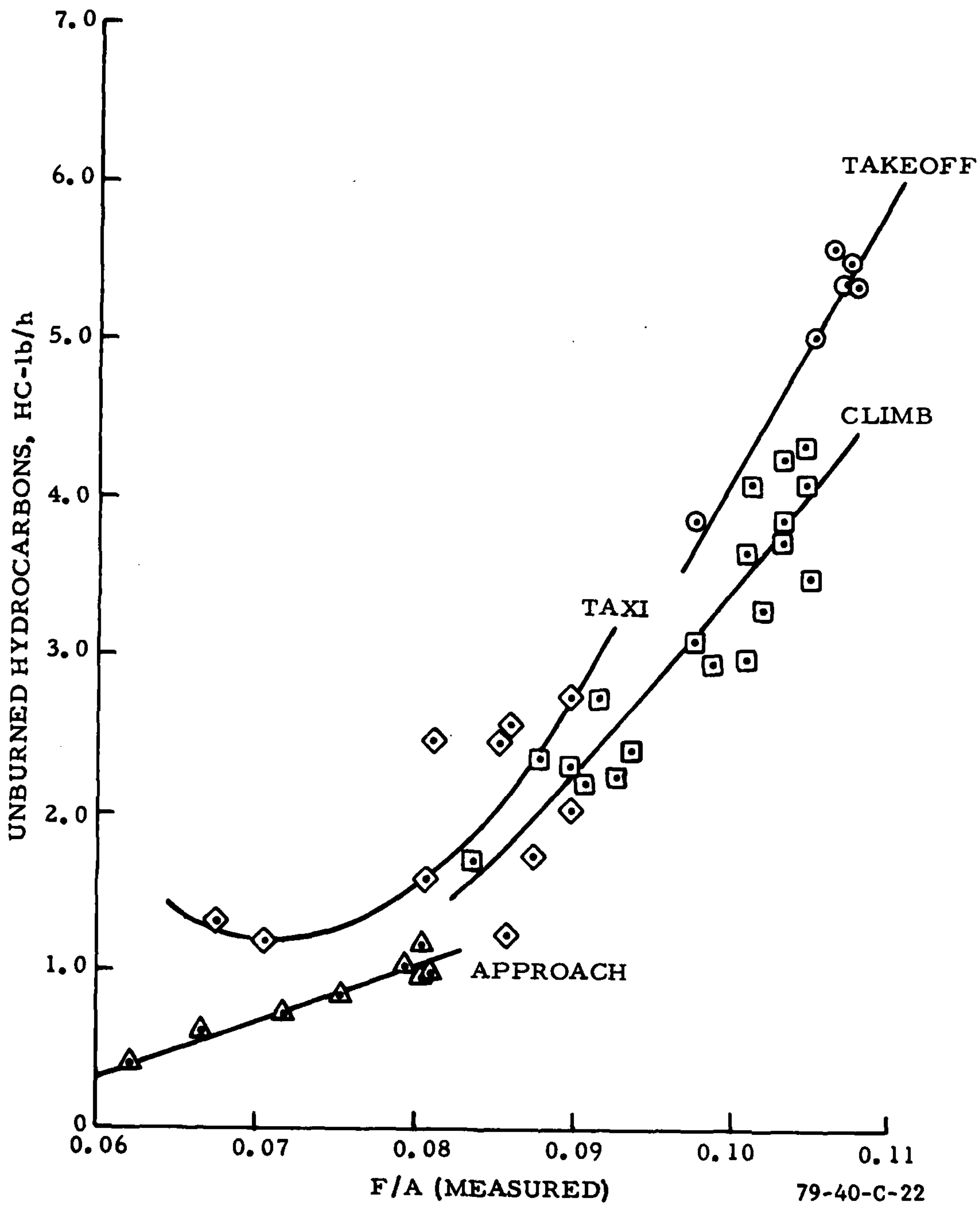

FIGURE C-22. SEA LEVEL HOT-DAY (T_1=120° F) EMISSIONS CHARACTERISTICS FOR A TCM GTSIO-520-K ENGINE--UNBURNED HYDROCARBONS

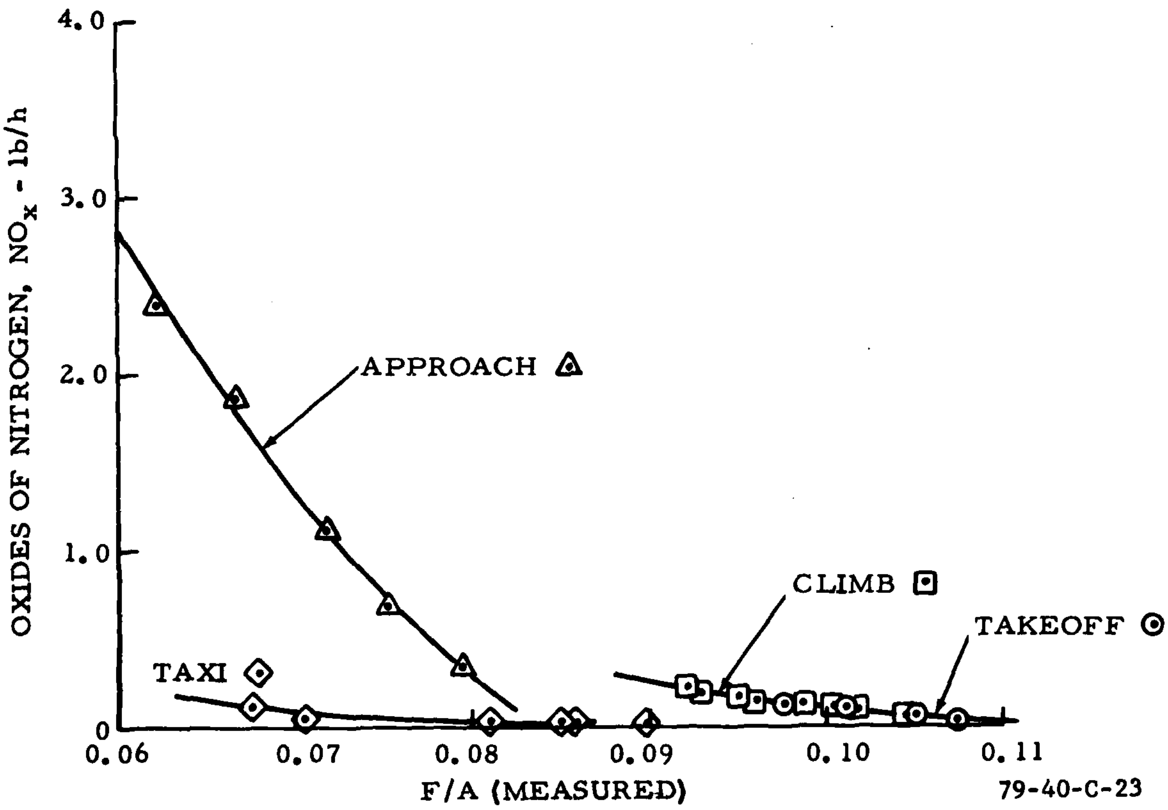

FIGURE C-23. SEA LEVEL HOT-DAY (T_i-120° F) EMISSIONS CHARACTERISTICS FOR A TCM GTSIO-520-K ENGINE--OXIDES OF NITROGEN

TABLE C-1. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--BASELINE 1--(NO IDLE, FIVE MODE)--
SPARK SETTING 20° BTC

	Run No.	2	3	4	5	6
Parameter	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
1. Act. Baro. - inHgA		30.17	30.17	30.17	30.17	30.17
2. Spec. Hum. - lb/lb		0.0115	0.0115	0.0115	0.0115	0.0115
3. Induct. Air Temp.-°F		72	72	71	72	72
4. Cooling Air Temp.-°F		72	76	76	77	74
5. Induct. Air Press.-inHgA		30.33	30.09	30.30	30.25	30.30
6. Engine Speed - RPM		1350	3400	3060	2600	1350
7. Manifold Air Press.-inHgA		14.5	44.4	36.5	24.0	14.0
8. Induct. Air Density-lb/ft^3		0.0756	0.0750	0.0756	0.0754	0.0755
9. Fuel Flow, W_f-lb/h		20.4	315.0	235.0	93.5	18.2
10. Airflow, W_a-lb/h		235.4	3045.0	2346.0	1185.0	219.0
11. F/A (Measured) = 9 / 10		0.0867	0.1034	0.1002	0.0789	0.0831
12. Max. Cht - °F		360	417	389	352	369
13. Avg. Cht - °F		321	377	356	333	328
14. Min. Cht - °F		253	349	330	311	250
15. EGT - °F		627	1301	1255	1223	701
16. Torque, lb-ft		118	890	800	500	112
17. Obs. Bhp		20	386	313	166	19
18. % CO_2 (Dry)		7.85	5.42	5.87	9.81	8.85
19. % CO (Dry)		9.91	13.86	13.07	6.47	7.44
20. % O_2 (Dry)		0.61	0.18	0.20	0.22	0.49
21. HC-ppm (Wet)		10,355	2502	2455	1557	5912
22. NO_x-ppm (Wet)		35	20	33	315	49
23. CO_2-lb/hr		28.5	269.5	222.0	170.4	31.0
24. CO-lb/hr		22.9	438.7	314.6	71.5	20.0
25. O_2-lb/hr		1.61	6.51	5.50	2.78	0.98
26. HC-lb/hr		1.57	5.20	3.88	1.15	0.735
27. NO_x-lb/hr		0.010	0.078	0.098	0.436	0.011
28. CO-lb/Mode		4.581	2.193	26.217	7.153	1.333
29. HC-lb/Mode		0.314	0.026	0.324	0.115	0.049
30. NO_x-lb/Mode		0.002	0.0004	0.008	0.044	0.0008

TABLE C-2. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--BASELINE 2--(NO IDLE, FIVE MODE)--SPARK SETTING 20° BTC

	Run No.	32	33	34	35	36
Parameter	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
1. Act. Baro. - inHgA		30.15	30.15	30.15	30.15	30.14
2. Spec. Hum. - lb/lb		0.0080	0.0080	0.0080	0.0008	0.0080
3. Induct. Air Temp.-°F		73	73	73	73	73
4. Cooling Air Temp.-°F		74	77	77	77	74
5. Induct. Air Press.-inHgA		30.32	30.08	30.28	30.32	30.30
6. Engine Speed - RPM		1360	3400	3060	2610	1350
7. Manifold Air Press.-inHgA		14.2	44.4	36.4	24.1	13.9
8. Induct. Air Density-lb/ft^3		0.0754	0.0748	0.0753	0.0754	0.0753
9. Fuel Flow, W_f-lb/h		19.5	315.0	233.0	94.0	19.2
10. Airflow, W_a-lb/h		233.3	3035.0	2326.0	1176.0	229.2
11. F/A (Measured) = 9 / 10		0.0836	0.1038	0.1002	0.0799	0.0838
12. Max. Cht - °F		357	415	392	353	348
13. Avg. Cht - °F		319	379	361	337	314
14. Min. Cht - °F		262	351	335	312	262
15. EGT - °F		752	1303	1262	1224	783
16. Torque, lb-ft		106	880	788	476	104
17. Obs. Bhp		18	382	308	158.5	18
18. % CO_2 (Dry)		8.49	5.40	5.92	9.77	8.80
19. % CO (Dry)		9.39	14.53	13.62	7.43	8.90
20. % O_2 (Dry)		0.40	0.17	0.20	0.22	0.37
21. HC-ppm (Wet)		5934	2355	2225	1408	5540
22. NO_x-ppm (Wet)		42	23	38	262	45
23. CO_2-lb/hr		30.5	272.6	226.2	172.2	30.8
24. CO-lb/hr		21.5	466.8	331.1	83.3	19.8
25. O_2-lb/hr		10.4	6.53	5.44	2.82	0.94
26. HC-lb/hr		0.881	4.88	3.49	1.04	0.808
27. NO_x-lb/hr		0.012	0.089	0.111	0.362	0.012
28. CO-lb/Mode		4.293	2.334	27.596	8.333	1.323
29. HC-lb/Mode		0.176	0.024	0.291	0.104	0.054
30. NO_x-lb/Mode		0.002	0.0004	0.009	0.036	0.0008

TABLE C-3. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--BASELINE 3--(NO IDLE, FIVE MODE)--
SPARK SETTING 20° BTC

	Run No.	902	903	904	905	906
Parameter	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
1. Act. Baro. - inHgA		30.16	30.16	30.16	30.16	30.16
2. Spec. Hum. - lb/lb		0.0110	0.0110	0.0110	0.0110	0.0110
3. Induct. Air Temp.-°F		74	73	74	73	73
4. Cooling Air Temp.-°F		74	78	78	77	75
5. Induct. Air Press.-inHgA		30.17	30.09	30.29	30.34	30.32
6. Engine Speed - RPM		1350	3400	3065	2610	1350
7. Manifold Air Press.-inHgA		14.5	44.5	36.4	24.0	13.9
8. Induct. Air Density-lb/ft^3		0.0749	0.0748	0.0747	0.0754	0.0754
9. Fuel Flow, W_f-lb/h		20.6	315.0	232.0	92.5	18.6
10. Airflow, W_a-lb/h		239.3	3036.0	2310.0	1181.0	228.2
11. F/A (Measured) = 9 / 10		0.0861	0.1038	0.1004	0.0783	0.0815
12. Max. Cht - °F		357	421	392	352	352
13. Avg. Cht - °F		320	384	360	338	317
14. Min. Cht - °F		230	353	334	312	269
15. EGT - °F		633	1302	1258	1224	798
16. Torque, lb-ft		--	880	786	478	--
17. Obs. Bhp		--	382	307	159	--
18. % CO_2 (Dry)		7.97	5.33	5.83	9.71	8.82
19. % CO (Dry)		8.48	14.20	13.21	5.92	6.76
20. % O_2 (Dry)		0.92	0.18	0.20	0.22	0.41
21. HC-ppm (Wet)		11,317	2267	2168	1340	5360
22. NO_x-ppm (Wet)		54	38	49	305	55
23. CO_2-lb/hr		28.7	266.1	218.0	166.2	29.4
24. CO-lb/hr		19.4	451.3	314.3	64.5	14.3
25. O_2-lb/hr		2.41	6.53	5.12	2.74	0.99
26. HC-lb/hr		1.74	4.70	3.38	0.99	0.77
27. NO_x-lb/hr		0.016	0.147	0.143	0.420	0.015
28. CO-lb/Mode		3.888	1.847	26.195	6.450	0.956
29. HC-lb/Mode		0.348	0.024	0.282	0.099	0.051
30. NO_x-lb/Mode		0.003	0.0007	0.012	0.042	0.001

TABLE C-4. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--BASELINE 4--(NO IDLE, FIVE MODE)--SPARK SETTING 20° BTC

Parameter	Run No.	913	914	915	916	917
	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
1. Act. Baro. - inHgA		30.08	30.08	30.08	30.08	30.07
2. Spec. Hum. - lb/lb		0.0105	0.0105	0.0105	0.0105	0.0105
3. Induct. Air Temp.-°F		102	117	119	122	120
4. Cooling Air Temp.-°F		110	118	121	127	112
5. Induct. Air Press.-inHgA		29.99	30.55	30.76	30.45	30.00
6. Engine Speed - RPM		1350	3400	3060	2610	1350
7. Manifold Air Press.-inHgA		14.6	44.5	36.5	23.9	14.4
8. Induct. Air Density-lb/ft^3		0.0707	0.0702	0.0704	0.0693	0.0685
9. Fuel Flow, W_f-lb/h		20.5	315.0	232.0	91.0	19.8
10. Airflow, W_a-lb/h		238.8	2971.0	2253.0	1128.0	232.8
11. F/A (Measured) = 9 / 10		0.0858	0.1060	0.1030	0.0807	0.0851
12. Max. Cht - °F		349	438	396	383	358
13. Avg. Cht - °F		311	391	371	358	325
14. Min. Cht - °F		247	355	350	347	277
15. EGT - °F		725	1296	1253	1218	804
16. Torque, lb-ft		--	835	748	450	--
17. Obs. Bhp		--	362	292	150	--
18. % CO_2 (Dry)		8.23	4.98	5.42	9.48	8.44
19. % CO (Dry)		8.50	14.61	13.61	7.28	7.34
20. % O_2 (Dry)		1.36	0.17	0.20	0.21	1.60
21. HC-ppm (Wet)		16,723	2729	2514	1397	15,444
22. NO_x-ppm (Wet)		53	12	22	259	84
23. CO_2-lb/hr		29.8	244.6	198.3	158.7	29.4
24. CO-lb/hr		19.6	456.7	316.8	77.6	16.2
25. O_2-lb/hr		3.58	6.07	5.29	2.56	4.04
26. HC-lb/hr		2.56	5.58	3.85	0.992	2.30
27. NO_x-lb/hr		0.015	0.046	0.063	0.344	0.023
28. CO-lb/Mode		3.920	2.283	26.404	7.757	1.083
29. HC-lb/Mode		0.512	0.028	0.321	0.099	0.153
30. NO_x-lb/Mode		0.003	0.0002	0.005	0.034	0.002

TABLE C-5. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--BASELINE 5--(NO IDLE, FIVE MODE)--SPARK SETTING 20° BTC

	Parameter	Run No. / Mode	908 Taxi Out	909 Takeoff	910 Climb	911 Approach	912 Taxi In
1.	Act. Baro. - inHgA		30.22	30.22	30.22	30.22	30.22
2.	Spec. Hum. - lb/lb		0.0080	0.0080	0.0080	0.0080	0.0085
3.	Induct. Air Temp.-°F		109	116	130	122	116
4.	Cooling Air Temp.-°F		112	116	134	121	102
5.	Induct. Air Press.-inHgA		30.14	30.70	30.90	31.09	30.14
6.	Engine Speed - RPM		1340	3400	3065	2600	1360
7.	Manifold Air Press.-inHgA		14.5	44.5	36.5	24.1	14.4
8.	Induct. Air Density-lb/ft^3		0.0702	0.0706	0.0694	0.0708	0.0693
9.	Fuel Flow, W_f-lb/h		21.4	318.0	233.0	91.5	19.3
10.	Airflow, W_a-lb/h		238.6	2973.0	2231.0	1140.0	226.4
11.	F/A (Measured) = 9 / 10		0.0897	0.1070	0.1044	0.0803	0.0852
12.	Max. Cht - °F		361	426	404	375	372
13.	Avg. Cht - °F		324	388	376	354	330
14.	Min. Cht - °F		262	363	358	334	261
15.	EGT - °F		735	1298	1249	1210	712
16.	Torque, lb-ft		--	840	750	460	--
17.	Obs. Bhp		--	364	293	153	--
18.	% CO_2 (Dry)		7.71	4.98	5.29	9.12	8.96
19.	% CO (Dry)		10.08	15.29	14.33	8.20	6.93
20.	% O_2 (Dry)		1.22	0.17	0.20	0.22	1.43
21.	HC-ppm (Wet)		17,630	2676	2697	1641	16,829
22.	NO_x-ppm (Wet)		55	17	26	218	75
23.	CO_2-lb/hr		28.8	249.5	195.4	156.9	30.3
24.	CO-lb/hr		23.9	487.6	336.9	89.8	14.9
25.	O_2-lb/hr		3.31	6.19	5.37	2.75	3.51
26.	HC-lb/hr		2.73	5.50	4.12	1.17	2.44
27.	NO_x-lb/hr		0.016	0.065	0.074	0.292	0.020
28.	CO-lb/Mode		4.785	2.438	28.073	8.978	0.993
29.	HC-lb/Mode		0.547	0.0275	0.343	0.117	0.163
30.	NO_x-lb/Mode		0.003	0.0003	0.006	0.029	0.001

TABLE C-6. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--BASELINE 6--(NO IDLE, FIVE MODE)--SPARK SETTING 20° BTC

	Run No.	59	60	61	62	63
Parameter	**Mode**	**Taxi Out**	**Takeoff**	**Climb**	**Approach**	**Taxi In**
1. Act. Baro. - inHgA		30.17	30.17	30.17	30.17	30.15
2. Spec. Hum. - lb/lb		0.0100	0.0100	0.0100	0.0100	0.0100
3. Induct. Air Temp.-°F		108	119	117	114	115
4. Cooling Air Temp.-°F		103	116	118	113	110
5. Induct. Air Press.-inHgA		30.09	30.64	30.86	31.02	30.07
6. Engine Speed - RPM		1350	3400	3070	2600	1350
7. Manifold Air Press.-inHgA		14.6	44.4	36.6	24.1	14.2
8. Induct. Air Density-lb/ft^3		0.0702	0.0701	0.0709	0.0716	0.0693
9. Fuel Flow, W_f-lb/h		21.3	317.0	235.0	93.0	19.5
10. Airflow, W_a-lb/h		237.0	2967.0	2282.0	1155.0	227.0
11. F/A (Measured) = 9 / 10		0.0899	0.1068	0.1030	0.0805	0.0859
12. Max. Cht - °F		357	435	390	370	362
13. Avg. Cht - °F		325	386	366	350	330
14. Min. Cht - °F		265	357	343	327	282
15. EGT - °F		789	1299	1254	1222	833
16. Torque, lb-ft		--	830	745	462	--
17. Obs. Bhp		--	360	292	153	--
18. % CO_2 (Dry)		7.71	4.98	5.38	9.36	8.42
19. % CO (Dry)		9.61	14.68	13.87	7.64	8.62
20. % O_2 (Dry)		1.02	0.17	0.20	0.21	0.70
21. HC-ppm (Wet)		13,196	2616	2402	1313	8456
22. NO_x-ppm (Wet)		43	14	23	240	44
23. CO_2-lb/hr		27.7	244.7	200.3	161.4	29.0
24. CO-lb/hr		22.0	459.1	328.7	83.9	18.9
25. O_2-lb/hr		2.67	6.07	5.41	2.63	1.75
26. HC-lb/hr		2.03	5.36	3.73	0.954	1.23
27. NO_x-lb/hr		0.012	0.054	0.067	0.326	0.012
28. CO-lb/Mode		4.394	2.295	27.388	8.385	1.258
29. HC-lb/Mode		0.407	0.447	0.311	0.095	0.082
30. NO_x-lb/Mode		0.0025	0.0003	0.006	0.033	0.008

TABLE C-7. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--BASELINE 7--(NO IDLE, FIVE MODE)--SPARK SETTING 20° BTC

Parameter	Run No. / Mode	64	65	66	67	68
		Taxi Out	Takeoff	Climb	Approach	Taxi In
1. Act. Baro. - inHgA		29.81	29.81	29.81	29.81	29.80
2. Spec. Hum. - lb/lb		0.0100	0.0100	0.0100	0.0100	0.0100
3. Induct. Air Temp.-°F		115	115	115	119	119
4. Cooling Air Temp.-°F		120	112	114	122	116
5. Induct. Air Press.-inHgA		29.72	30.25	30.46	30.56	29.72
6. Engine Speed - RPM		1360	3400	3070	2600	1350
7. Manifold Air Press.-inHgA		14.6	44.4	36.5	24.0	14.4
8. Induct. Air Density-lb/ft^3		0.0685	0.0697	0.0702	0.0699	0.0680
9. Fuel Flow, W_f-lb/h		21.4	315.0	233.0	92.5	18.8
10. Airflow, W_a-lb/h		245.2	2954.0	2258.0	1173.0	233.2
11. F/A (Measured) = 9 / 10		0.0873	0.1066	0.1032	0.0789	0.0806
12. Max. Cht - °F		362	418	389	375	370
13. Avg. Cht - °F		326	382	366	355	334
14. Min. Cht - °F		279	355	341	331	278
15. EGT - °F		761	1262	1230	1188	747
16. Torque, lb-ft		--	820	745	454	--
17. Obs. Bhp		--	356	292	151	--
18. % CO_2 (Dry)		8.00	4.87	5.37	9.35	9.12
19. % CO (Dry)		10.40	14.99	14.30	7.58	8.03
20. % O_2 (Dry)		0.73	0.16	0.19	0.20	0.90
21. HC-ppm (Wet)		11,295	3222	2770	1599	10,666
22. NO_x-ppm (Wet)		58	11	25	283	103
23. CO_2-lb/hr		30.8	239.7	199.9	163.5	32.2
24. CO-lb/hr		25.5	469.6	338.8	84.4	18.1
25. O_2-lb/hr		2.04	5.72	5.22	2.54	2.31
26. HC-lb/hr		1.78	6.56	4.26	1.17	1.57
27. NO_x-lb/hr		0.017	0.042	0.072	0.388	0.028
28. CO-lb/Mode		5.092	2.737	28.234	8.435	1.204
29. HC-lb/Mode		0.357	0.033	0.355	0.117	0.104
30. NO_x-lb/Mode		0.003	0.0002	0.006	0.039	0.002

TABLE C-8. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--BASELINE 8--(NO IDLE, FIVE MODE)--
SPARK SETTING 20° BTC

	Run No.	75	76	77	78	79
Parameter	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
1. Act. Baro. - inHgA		29.81	29.81	29.81	29.81	29.81
2. Spec. Hum. - lb/lb		0.0055	0.0055	0.0055	0.0055	0.0055
3. Induct. Air Temp.-°F		63	61	62	62	61
4. Cooling Air Temp.-°F		58	61	62	62	59
5. Induct. Air Press.-inHgA		29.96	29.72	29.93	30.13	30.14
6. Engine Speed - RPM		1350	3400	3060	2600	1360
7. Manifold Air Press.-inHgA		14.2	44.4	36.7	24.1	13.9
8. Induct. Air Density-lb/ft^3		0.0759	0.0756	0.0760	0.0765	0.0767
9. Fuel Flow, W_f-lb/h		20.9	322.0	236.0	93.5	20.5
10. Airflow, W_a-lb/h		239.1	3078.0	2375.0	1185.0	237.5
11. F/A (Measured) = 9 / 10		0.0874	0.1046	0.0994	0.0789	0.0863
12. Max. Cht - °F		349	405	383	341	343
13. Avg. Cht - °F		307	367	348	326	306
14. Min. Cht - °F		250	340	314	300	250
15. EGT - °F		709	1281	1246	1206	744
16. Torque, lb-ft		--	900	820	488	--
17. Obs. Bhp		--	390	320	162	--
18. % CO_2 (Dry)		7.67	5.18	5.80	9.69	8.20
19. % CO (Dry)		11.24	14.50	13.40	6.60	10.77
20. % O_2 (Dry)		0.37	0.17	0.19	0.21	0.42
21. HC-ppm (Wet)		5993	2472	2298	1442	50[illegible]3
22. NO_x-ppm (Wet)		32	18	37	371	45
23. CO_2-lb/hr		29.2	264.9	224.9	169.4	30.9
24. CO-lb/hr		27.2	472.0	330.8	73.4	25.8
25. O_2-lb/hr		1.02	6.32	5.36	2.67	1.15
26. HC-lb/hr		0.924	5.21	3.67	1.07	0.770
27. NO_x-lb/hr		0.009	0.071	0.111	0.514	0.013
28. CO-lb/Mode		5.444	2.673	27.536	7.344	1.723
29. HC-lb/Mode		0.185	0.026	0.306	0.107	0.051
30. NO_x-lb/Mode		0.002	0.0004	0.009	0.051	0.001

TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--BASELINE 9--(NO IDLE, FIVE MODE)--
SPARK SETTING 20° BTC

	Parameter	Run No. / Mode	99 Taxi Out	100 Takeoff	101 Climb	102 Approach	103 Taxi In
1.	Act. Baro. - inHgA		29.80	29.80	29.80	29.80	29.79
2.	Spec. Hum. - lb/lb		0.0055	0.0055	0.0055	0.0055	0.0060
3.	Induct. Air Temp.-°F		62	62	62	63	62
4.	Cooling Air Temp.-°F		59	64	65	65	62
5.	Induct. Air Press.-inHgA		29.96	29.72	29.92	30.13	29.95
6.	Engine Speed - RPM		1340	3400	3060	2600	1350
7.	Manifold Air Press.-inHgA		14.0	44.3	36.4	23.9	13.9
8.	Induct. Air Density-lb/ft^3		0.0761	0.0755	0.0760	0.0763	0.0760
9.	Fuel Flow, W_f-lb/h		20.6	321.0	235.0	93.0	20.3
10.	Airflow, W_a-lb/h		232.2	3073.0	2383.0	1192.0	231.3
11.	F/A (Measured) = 9 / 10		0.0887	0.1045	0.0986	0.0780	0.0878
12.	Max. Cht - °F		349	415	387	344	343
13.	Avg. Cht - °F		304	369	352	327	306
14.	Min. Cht - °F		242	343	320	303	255
15.	EGT - °F		640	1276	1247	1206	761
16.	Torque, lb-ft		--	895	808	500	--
17.	Obs. Bhp		--	388	315	166	--
18.	% CO_2 (Dry)		7.90	5.27	6.01	10.01	8.18
19.	% CO (Dry)		10.15	14.34	13.09	6.68	9.43
20.	% O_2 (Dry)		0.52	0.18	0.20	0.22	0.40
21.	HC-ppm (Wet)		8000	2418	2288	1731	5583
22.	NO_x-ppm (Wet)		29	18	37	373	37
23.	CO_2-lb/hr		28.6	268.8	232.9	177.2	29.1
24.	CO-lb/hr		23.4	465.5	322.8	75.3	21.4
25.	O_2-lb/hr		1.37	6.68	5.64	2.83	1.03
26.	HC-lb/hr		1.20	5.08	3.66	1.28	0.833
27.	NO_x-lb/hr		0.008	0.071	0.110	0.518	0.010
28.	CO-lb/Mode		4.676	2.328	26.904	7.528	1.424
29.	HC-lb/Mode		0.240	0.025	0.305	0.128	0.056
30.	NO_x-lb/Mode		0.002	0.0004	0.009	0.052	0.001

TABLE C-10. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--TAKEOFF MODE--SPARK SETTING 20° BTC

	Run No.	22	23	24	25
Parameter	**Mode**	**Takeoff**	**Takeoff**	**Takeoff**	**Takeoff**
1. Act. Baro. - inHgA		30.19	30.19	30.19	30.18
2. Spec. Hum. - lb/lb		0.0105	0.0105	0.0105	0.0105
3. Induct. Air Temp.-°F		74	74	73	73
4. Cooling Air Temp.-°F		79	79	79	78
5. Induct. Air Press.-inHgA		30.11	30.12	30.12	30.12
6. Engine Speed - RPM		3400	3400	3400	3400
7. Manifold Air Press.-inHgA		44.4	44.5	44.4	44.4
8. Induct. Air Density-lb/ft^3		0.0747	0.0748	0.0749	0.0749
9. Fuel Flow, W_f-lb/hr		314.0	304.0	294.0	284.0
10. Airflow, W_a-lb/hr		3034.0	3036.0	3038.0	3022.0
11. F/A (Measured) = 9 / 10		0.1035	0.1001	0.0968	0.0940
12. Max. Cht - °F		422	438	456	472
13. Avg. Cht - °F		383	399	412	427
14. Min. Cht - °F		357	369	382	398
15. EGT - °F		1305	1321	1346	1372
16. Torque, lb-ft		888	890	904	920
17. Obs. Bhp		385	386	392	399
18. % CO_2 (Dry)		5.35	5.72	6.15	6.70
19. % CO (Dry)		14.22	13.45	12.62	11.63
20. % O_2 (Dry)		0.18	0.17	0.16	0.15
21. HC-ppm (Wet)		2413	1972	1740	1513
22. NO_x-ppm (Wet)		19	27	36	47
23. CO_2-lb/hr		267.3	282.0	298.6	318.9
24. CO-lb/hr		452.1	422.0	390.0	352.3
25. O_2-lb/hr		6.54	6.09	5.65	5.19
26. HC-lb/hr		4.99	4.03	3.52	3.02
27. NO_x-lb/hr		0.074	0.103	0.136	0.175
28. CO-lb/Mode		2.261	2.110	1.950	1.762
29. HC-lb/Mode		0.025	0.020	0.018	0.015
30. NO_x-lb/Mode		0.0004	0.0005	0.0007	0.0009

TABLE C-11. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--TAKEOFF MODE--SPARK SETTING 20° BTC

	Run No.	50	51	52	53
Parameter	Mode	Takeoff	Takeoff	Takeoff	Takeoff
1. Act. Baro. - inHgA		30.14	30.14	30.14	30.14
2. Spec. Hum. - lb/lb		0.0105	0.0105	0.0105	0.0105
3. Induct. Air Temp.-°F		127	132	127	128
4. Cooling Air Temp.-°F		125	131	123	127
5. Induct. Air Press.-inHgA		30.60	30.58	30.60	30.60
6. Engine Speed - RPM		3400	3400	3405	3400
7. Manifold Air Press.-inHgA		44.4	44.3	44.4	44.5
8. Induct. Air Density-lb/ft^3		0.0691	0.0685	0.0691	0.0690
9. Fuel Flow, W_f-lb/hr		315.0	305.0	295.0	285.0
10. Airflow, W_a-lb/hr		2929.0	2906.0	2918.0	2923.0
11. F/A (Measured) = 9 / 10		0.1075	0.1050	0.1011	0.0975
12. Max. Cht - °F		434	452	487	497
13. Avg. Cht - °F		392	405	422	434
14. Min. Cht - °F		361	376	389	397
15. EGT - °F		1300	1308	1324	1354
16. Torque, lb-ft		810	820	850	870
17. Obs. Bhp		351	356	369	377
18. % CO_2 (Dry)		4.86	5.03	5.74	6.16
19. % CO (Dry)		15.38	15.09	13.74	13.13
20. % O_2 (Dry)		0.18	0.18	0.17	0.16
21. HC-ppm (Wet)		2646	2526	2076	1981
22. NO_x-ppm (Wet)		10	14	27	32
23. CO_2-lb/hr		239.3	244.6	273.9	291.8
24. CO-lb/hr		481.9	467.0	417.2	395.9
25. O_2-lb/hr		6.44	6.36	5.90	5.51
26. HC-lb/hr		5.36	5.03	4.10	3.86
27. NO_x-lb/hr		0.038	0.052	0.100	0.117
28. CO-lb/Mode		2.409	2.33[illegible]	2.086	1.979
29. HC-lb/Mode		0.027	0.025	0.020	0.019
30. NO_x-lb/Mode		0.0002	0.0003	0.0005	0.0006

TABLE C-12. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--TAKEOFF MODE--SPARK SETTING 20° BTC

	Run No.	80	81	82	83
Parameter	Mode	Takeoff	Takeoff	Takeoff	Takeoff
1. Act. Baro. - inHgA		29.81	29.81	29.81	29.81
2. Spec. Hum. - lb/lb		0.0055	0.0055	0.0055	0.0055
3. Induct. Air Temp.-°F		60	61	60	61
4. Cooling Air Temp.-°F		62	62	62	62
5. Induct. Air Press.-inHgA		29.73	29.74	29.72	29.74
6. Engine Speed - RPM		3400	3400	3400	3400
7. Manifold Air Press.-inHgA		44.3	44.1	44.3	44.1
8. Induct. Air Density-lb/ft^3		0.0758	0.0756	0.0757	0.0756
9. Fuel Flow, W_f-lb/hr		320.0	310.0	300.0	290.0
10. Airflow, W_a-lb/hr		3087.0	3061.0	3089.0	3027.0
11. F/A (Measured) = 9 / 10		0.1037	0.1013	0.0971	0.0958
12. Max. Cht - °F		407	421	437	447
13. Avg. Cht - °F		371	382	392	405
14. Min. Cht - °F		341	351	364	378
15. EGT - °F		1279	1295	1316	1339
16. Torque, lb-ft		905	910	915	920
17. Obs. Bhp		393	395	397	399
18. % CO_2 (Dry)		5.32	5.75	6.10	6.68
19. % CO (Dry)		14.30	13.80	12.60	12.20
20. % O_2 (Dry)		0.18	0.17	0.17	0.15
21. HC-ppm (Wet)		2466	2217	2109	1415
22. NO_x-ppm (Wet)		20	30	37	48
23. CO_2-lb/hr		272.5	289.7	302.4	324.1
24. CO-lb/hr		466.2	442.5	397.6	376.8
25. O_2-lb/hr		6.70	6.23	6.13	5.29
26. HC-lb/hr		5.19	4.67	4.34	2.84
27. NO_x-lb/hr		0.079	0.116	0.143	0.180
28. CO-lb/Mode		2.331	2.213	1.988	1.884
29. HC-lb/Mode		0.026	0.023	0.022	0.014
30. NO_x-lb/Mode		0.0004	0.0006	0.0007	0.0009

TABLE C-13. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--CLIMB MODE--
SPARK SETTING 20° BTC

	Parameter	Run No.	13	14	15	16	17	18
		Mode	Climb	Climb	Climb	Climb	Climb	Climb
1.	Act. Baro. - inHgA		30.18	30.18	30.18	30.18	30.18	30.19
2.	Spec. Hum. - lb/lb		0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
3.	Induct. Air Temp.-°F		74	74	74	74	74	74
4.	Cooling Air Temp.-°F		79	79	79	79	79	79
5.	Induct. Air Press.-inHgA		30.31	30.31	30.31	30.32	30.32	30.33
6.	Engine Speed - RPM		3060	3060	3060	3050	3060	3060
7.	Manifold Air Press.-inHgA		36.5	36.5	36.6	36.4	36.5	36.5
8.	Induct. Air Density-lb/ft^3		0.0752	0.0752	0.0752	0.0752	0.0752	0.0753
9.	Fuel Flow, W_f-lb/h		236.0	226.0	216.0	206.0	196.0	186.0
10.	Airflow, W_a-lb/h		2333.0	2316.0	2297.0	2282.0	2269.0	2266.0
11.	F/A (Measured) = 9 / 10		0.1012	0.0976	0.0940	0.0903	0.0864	0.0821
12.	Max. Cht - °F		388	407	423	436	456	472
13.	Avg. Cht - °F		358	374	386	400	416	429
14.	Min. Cht - °F		336	350	357	368	380	394
15.	EGT - °F		1257	1285	1310	1335	1369	1399
16.	Torque, lb-ft		812	818	830	834	842	840
17.	Obs. Bhp		317	319	324	324	329	328
18.	% CO_2 (Dry)		5.76	6.55	7.00	7.57	8.39	9.04
19.	% CO (Dry)		13.39	11.95	11.06	10.03	8.65	7.49
20.	% O_2 (Dry)		0.20	0.18	0.18	0.17	0.16	0.16
21.	HC-ppm (Wet)		2331	2074	1278	1264	1275	1150
22.	NO_x-ppm (Wet)		30	52	68	92	144	217
23.	CO_2-lb/hr		218.5	240.0	250.8	264.8	286.5	303.5
24.	CO-lb/hr		323.3	278.7	252.2	223.3	188.0	160.1
25.	O_2-lb/hr		5.52	4.80	4.69	4.32	3.97	3.91
26.	HC-lb/hr		3.68	3.21	1.94	1.88	1.86	1.65
27.	NO_x-lb/hr		0.089	0.151	0.193	0.256	0.393	0.582
28.	CO-lb/Mode		26.943	23.228	21.0[illegible]6	18.611	15.668	13.338
29.	HC-lb/Mode		0.307	0.267	0.161	0.157	0.155	0.137
30.	NO_x-lb/Mode		0.0074	0.0126	0.0161	0.0213	0.0328	0.0485

TABLE C-14. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--CLIMB MODE--SPARK SETTING20° BTC

Parameter	Run No.	42	43	44	45	46	47	48	49
	Mode	Climb	Climb	Climb	Climb	Climb	Climb	Climb	Climb
1. Act. Baro. - inHgA		30.15	30.15	30.15	30.15	30.15	30.15	30.15	30.14
2. Spec. Hum. - lb/lb		0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
3. Induct. Air Temp.-°F		124	127	131	127	128	132	128	129
4. Cooling Air Temp.-°F		123	128	131	124	128	132	125	128
5. Induct. Air Press.-inHgA		30.82	30.81	30.80	30.81	30.82	30.81	30.83	30.82
6. Engine Speed - RPM		3060	3065	3065	3070	3070	3070	3060	3060
7. Manifold Air Press.-inHgA		36.4	36.6	36.5	36.5	36.4	36.5	36.6	36.5
8. Induct. Air Density-lb/ft^3		0.0699	0.0696	0.0691	0.0696	0.0696	0.0695	0.0690	0.0693
9. Fuel Flow, W_f-lb/hr		235.0	230.0	225.0	220.0	215.0	210.0	205.0	200.0
10. Airflow, W_a-lb/hr		2245.0	2261.0	2236.0	2230.0	2243.0	2210.0	2208.0	2170.0
11. F/A (Measured) = 9 / 10		0.1047	0.1017	0.1006	0.0987	0.0959	0.0950	0.0950	0.0922
12. Max. Cht - °F		390	400	412	421	427	433	438	445
13. Avg. Cht - °F		366	372	383	389	397	403	409	413
14. Min. Cht - °F		347	352	360	363	370	375	380	385
15. EGT - °F		1247	1259	1274	1292	1305	1313	1329	1335
16. Torque, lb-ft		745	748	752	758	760	766	770	762
17. Obs. Bhp		291	292	294	297	298	299	301	297
18. % CO_2 (Dry)		5.37	5.57	5.96	6.32	6.58	6.82	7.10	7.46
19. % CO (Dry)		14.24	13.91	13.16	12.62	12.22	11.81	10.84	10.23
20. % O_2 (Dry)		0.21	0.20	0.19	0.19	0.18	0.18	0.18	0.17
21. HC-ppm (Wet)		2280	2154	1978	1979	1615	1551	1525	1642
22. NO_x-ppm (Wet)		24	27	38	47	52	61	68	83
23. CO_2-lb/hr		199.1	206.6	215.6	225.7	235.3	238.9	243.8	249.2
24. CO-lb/hr		336.0	328.3	302.9	286.9	278.1	263.3	236.9	219.0
25. O_2-lb/hr		5.66	5.39	5.00	4.93	4.68	4.59	4.24	4.13
26. HC-lb/hr		3.50	3.30	2.98	2.96	2.40	2.26	2.19	2.32
27. NO_x-lb/hr		0.069	0.077	0.107	0.131	0.145	0.166	0.183	02.19
28. CO-lb/Mode		28.002	27.362	25.245	23.906	23.174	21.943	19.943	18.248
29. HC-lb/Mode		0.292	0.275	0.249	0.246	0.200	0.188	0.182	0.193
30. NO_x-lb/Mode		0.0058	0.0064	0.0089	0.0110	0.0121	0.0139	0.0153	0.0183

TABLE C-15. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--CLIMB MODE--
SPARK SETTING 20° BTC

	Run No.	69	70	71	72	73	74
Parameter	Mode	Climb	Climb	Climb	Climb	Climb	Climb
1. Act. Baro. - inHgA		29.80	29.80	29.80	29.80	29.80	29.80
2. Spec. Hum. - lb/lb		0.0095	0.0095	0.0095	0.0095	0.0095	0.0095
3. Induct. Air Temp.-°F		116	118	115	117	119	116
4. Cooling Air Temp.-°F		115	116	113	117	117	113
5. Induct. Air Press.-inHgA		30.45	30.45	30.46	30.45	30.45	30.45
6. Engine Speed - RPM		3060	3060	3070	3060	3060	3070
7. Manifold Air Press.-inHgA		36.6	36.3	36.5	36.5	36.6	36.6
8. Induct. Air Density-lb/ft^3		0.0701	0.0698	0.0702	0.0699	0.0697	0.0701
9. Fuel Flow, W_f-lb/h		236.0	226.0	217.0	205.0	196.0	186.0
10. Airflow, W_a-lb/h		2265.0	2242.0	2225.0	2245.0	2223.0	2224.0
11. F/A (Measured) = 9 / 10		0.1042	0.1008	0.0975	0.0913	0.0877	0.0836
12. Max. Cht - °F		389	405	418	433	454	469
13. Avg. Cht - °F		364	378	385	400	416	427
14. Min. Cht - °F		339	352	362	376	392	401
15. EGT - °F		1232	1252	1279	1312	1341	1380
16. Torque, lb-ft		745	754	770	774	785	800
17. Obs. Bhp		291	294	302	302	306	313
18. % CO_2 (Dry)		5.50	5.96	6.50	7.35	7.98	8.63
19. % CO (Dry)		14.00	13.00	12.00	10.50	9.45	8.40
20. % O_2 (Dry)		0.20	0.20	0.18	0.17	0.16	0.15
21. HC-ppm (Wet)		2797	2427	2083	1859	1634	1183
22. NO_x-ppm (Wet)		27	41	63	88	123	181
23. CO_2-lb/hr		204.9	215.9	229.1	255.2	271.6	288.4
24. CO-lb/hr		331.9	299.7	269.2	232.0	204.7	178.7
25. O_2-lb/hr		5.42	5.27	4.61	4.29	3.96	3.64
26. HC-lb/hr		4.33	3.67	3.10	2.73	2.35	1.67
27. NO_x-lb/hr		0.078	0.116	0.175	0.241	0.332	0.479
28. CO-lb/Mode		27.661	24.978	22.431	19.337	17.055	14.890
29. HC-lb/Mode		0.361	0.306	0.258	0.227	0.196	0.139
30. NO_x-lb/Mode		0.0065	0.0097	0.0146	0.0201	0.0276	0.0399

TABLE C-16. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--CLIMB MODE--
SPARK SETTING 20° BTC

	Run No.	84	85	86	87	88	89
Parameter	Mode	Climb	Climb	Climb	Climb	Climb	Climb
1. Act. Baro. - inHgA		29.81	29.81	29.81	29.81	29.81	29.80
2. Spec. Hum. - lb/lb		0.0060	0.0060	0.0060	0.0060	0.0060	0.0060
3. Induct. Air Temp.-°F		61	60	60	61	61	61
4. Cooling Air Temp.-°F		62	62	62	63	62	62
5. Induct. Air Press.-inHgA		29.93	29.94	29.94	29.94	29.94	29.93
6. Engine Speed - RPM		3060	3060	3060	3060	3060	3060
7. Manifold Air Press.-inHgA		36.5	36.5	36.4	36.6	36.7	36.4
8. Induct. Air Density-lb/ft^3		0.0761	0.0763	0.0763	0.0762	0.0762	0.0761
9. Fuel Flow, W_f-lb/h		236.0	226.0	216.0	206.0	196.0	186.0
10. Airflow, W_a-lb/h		2374.0	2371.0	2356.0	2351.0	2357.0	2321.0
11. F/A (Measured) = 9 / 10		0.0994	0.0953	0.0917	0.0876	0.0832	0.0801
12. Max. Cht - °F		383	397	416	434	452	465
13. Avg. Cht - °F		349	362	377	393	408	419
14. Min. Cht - °F		316	327	341	352	365	376
15. EGT - °F		1246	1276	1304	1336	1375	1405
16. Torque, lb-ft		810	825	828	840	842	846
17. Obs. Bhp		316	322	323	328	329	330
18. % CO_2 (Dry)		5.91	6.60	7.29	7.92	8.94	9.64
19. % CO (Dry)		13.57	11.50	10.50	9.50	7.80	6.60
20. % O_2 (Dry)		0.19	0.17	0.18	0.16	0.15	0.15
21. HC-ppm (Wet)		2366	2031	1605	1569	1306	1122
22. NO_x-ppm (Wet)		45	63	104	142	248	396
23. CO_2-lb/hr		230.2	246.2	266.4	285.1	315.4	329.5
24. CO-lb/hr		336.4	273.1	244.2	217.7	175.1	143.6
25. O_2-lb/hr		5.38	4.61	4.78	4.19	3.85	3.73
26. HC-lb/hr		3.78	3.19	2.47	2.38	1.96	1.63
27. NO_x-lb/hr		0.134	0.185	0.299	0.403	0.695	1.079
28. CO-lb/Mode		28.032	22.756	20.350	18.139	14.594	11.964
29. HC-lb/Mode		0.315	0.266	0.206	0.198	0.163	0.136
30. NO_x-lb/Mode		0.0112	0.0154	0.0250	0.0336	0.0579	0.0899

TABLE C-17. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--APPROACH MODE--SPARK SETTING 20° BTC

	Run No.	8	9	10	11	12
Parameter	Mode	Approach	Approach	Approach	Approach	Approach
1. Act. Baro. - inHgA		30.18	30.18	30.18	30.18	30.18
2. Spec. Hum. - lb/lb		0.0060	0.0060	0.0060	0.0060	0.0060
3. Induct. Air Temp.-°F		72	73	73	73	73
4. Cooling Air Temp.-°F		78	77	78	77	78
5. Induct. Air Press.-inHgA		30.35	30.36	30.36	30.37	30.38
6. Engine Speed - RPM		2600	2600	2610	2600	2610
7. Manifold Air Press.-inHgA		24.0	24.0	24.1	24.1	24.1
8. Induct. Air Density-lb/ft^3		0.0756	0.0755	0.0755	0.0755	0.0755
9. Fuel Flow, W_f-lb/h		94.0	90.0	86.0	82.0	78.0
10. Airflow, W_a-lb/h		1186.0	1181.0	1190.0	1134.0	1169.0
11. F/A (Measured) = 9 / 10		0.0793	0.0762	0.0723	0.0723	0.0667
12. Max. Cht - °F		354	357	362	368	373
13. Avg. Cht - °F		334	337	343	349	353
14. Min. Cht - °F		311	314	319	322	326
15. EGT - °F		1221	1243	1273	1307	1332
16. Torque, lb-ft		500	500	505	496	478
17. Obs. Bhp		166	166	168	165	159
18. % CO_2 (Dry)		9.92	10.47	11.45	12.16	12.80
19. % CO (Dry)		6.80	5.77	4.17	3.07	2.06
20. % O_2 (Dry)		0.22	0.23	0.26	0.29	0.34
21. HC-ppm (Wet)		1530	1395	1205	1113	989
22. NO_x-ppm (Wet)		328	452	799	1178	1550
23. CO_2-lb/hr		174.8	181.0	185.3	196.8	211.8
24. CO-lb/hr		76.2	63.5	45.6	31.6	21.7
25. O_2-lb/hr		2.82	2.89	3.24	3.41	4.09
26. HC-lb/hr		1.14	1.02	0.875	0.770	0.689
27. NO_x-lb/hr		0.456	0.618	1.085	1.524	2.021
28. CO-lb/Mode		7.625	6.350	4.556	3.162	2.170
29. HC-lb/Mode		0.114	0.102	0.0875	0.0770	0.0689
30. NO_x-lb/Mode		0.0456	0.0618	0.1085	0.1524	0.2021

TABLE C-18. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--APPROACH MODE--SPARK SETTING 20° BTC

Parameter	Mode	Run No. 37 Approach	38 Approach	39 Approach	40 Approach	41 Approach
1. Act. Baro. ~ inHgA		30.22	30.22	30.22	30.22	30.21
2. Spec. Hum. - lb/lb		0.0090	0.0090	0.0090	0.0090	0.0090
3. Induct. Air Temp.-°F		117	118	114	116	113
4. Cooling Air Temp.-°F		116	118	112	116	110
5. Induct. Air Press.-inHgA		31.11	31.10	31.12	31.12	31.13
6. Engine Speed - RPM		2600	2600	2600	2600	2600
7. Manifold Air Press.-inHgA		23.9	24.1	24.2	24.2	24.0
8. Induct. Air Density-lb/ft^3		0.0715	0.0713	0.0719	0.0716	0.0720
9. Fuel Flow, W_f-lb/h		91.0	86.0	81.0	75.5	71.0
10. Airflow, W_a-lb/h		1146.0	1144.0	1128.0	1134.0	1141.0
11. F/A (Measured) = 9 / 10		0.0794	0.0752	0.0718	0.0666	0.0622
12. Max. Cht - °F		361	384	385	395	390
13. Avg. Cht - °F		345	361	365	372	368
14. Min. Cht - °F		324	338	341	347	345
15. EGT ~ °F		1207	1249	1295	1336	1363
16. Torque, lb-ft		448	454	464	455	448
17. Obs. Bhp		149	151	154	151	149
18. % CO_2 (Dry)		9.49	10.60	11.54	12.68	13.40
19. % CO (Dry)		7.72	5.73	4.14	2.34	1.03
20. % O_2 (Dry)		0.22	0.22	0.24	0.30	0.43
21. HC-ppm (Wet)		1435	1178	1080	891	571
22. NO_x-ppm (Wet)		251	513	865	1479	1890
23. CO_2-lb/hr		163.1	177.2	187.4	203.6	214.4
24. CO-lb/hr		84.4	61.0	42.8	23.9	10.5
25. O_2-lb/hr		2.75	2.68	2.84	3.50	5.00
26. HC-lb/hr		1.03	0.830	0.739	0.602	0.387
27. NO_x-lb/hr		0.337	0.676	1.107	1.87	2.395
28. CO-lb/Mode		8.444	6.095	4.280	2.392	1.049
29. HC-lb/Mode		0.103	0.0830	0.0739	0.0602	0.0388
30. NO_x-lb/Mode		0.0337	0.0676	0.1107	0.187	0.2395

TABLE C-19. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--APPROACH MODE--SPARK SETTING 20° BTC

	Run No.	90	91	92	93	94
Parameter	Mode	Approach	Approach	Approach	Approach	Approach
1. Act. Baro. - inHgA		29.80	29.80	29.80	29.80	29.80
2. Spec. Hum. - lb/lb		0.0055	0.0055	0.0055	0.0055	0.0055
3. Induct. Air Temp.-°F		62	62	61	61	61
4. Cooling Air Temp.-°F		63	62	63	63	62
5. Induct. Air Press.-inHgA		30.13	30.13	30.13	30.13	30.13
6. Engine Speed - RPM		2605	2600	2610	2605	2600
7. Manifold Air Press.-inHgA		23.9	23.9	24.1	24.2	24.1
8. Induct. Air Density-lb/ft^3		0.0765	0.0765	0.0766	0.0766	0.0766
9. Fuel Flow, W_f-lb/h		95.0	91.0	86.5	83.0	79.0
10. Airflow, W_a-lb/h		1189.0	1202.0	1203.0	1223.0	1207.0
11. F/A (Measured) = 9 / 10		0.0799	0.0757	0.0719	0.0679	0.0655
12. Max. Cht - °F		344	350	354	360	361
13. Avg. Cht - °F		326	331	335	341	341
14. Min. Cht - °F		302	306	310	314	315
15. EGT - °F		1203	1237	1264	1305	1324
16. Torque, lb-ft		490	492	488	490	492
17. Obs. Bhp		163	163	162	163	163
18. % CO_2 (Dry)		9.96	10.86	11.58	12.69	13.07
19. % CO (Dry)		6.51	4.57	3.06	1.86	1.61
20. % O_2 (Dry)		0.21	0.22	0.24	0.28	0.31
21. HC-ppm (Wet)		1461	1357	1248	980	840
22. NO_x-ppm (Wet)		366	654	981	1778	2184
23. CO_2-lb/hr		174.9	188.2	197.6	218.8	222.5
24. CO-lb/hr		72.8	50.4	33.2	20.4	17.4
25. O_2-lb/hr		2.68	2.77	2.98	3.51	3.84
26. HC-lb/hr		1.09	1.01	0.914	0.717	0.604
27. NO_x-lb/hr		0.511	0.908	1.344	2.432	2.937
28. CO-lb/Mode		7.275	5.042	3.323	2.041	1.745
29. HC-lb/Mode		0.109	0.138	0.0914	0.0717	0.0604
30. NO_x-lb/Mode		0.0511	0.0908	0.1344	0.2432	0.2937

TABLE C-20. TCM GTSIO-520-K ENGINE--NAFEC TEST DATA--TAXI MODE--SPARK SETTING 20° BTC

Parameter	Run No.	26	27	28	54	55	56	95	96	97	98
	Mode	Taxi	Taxi	Taxi	Taxi	Taxi	Taxi	Taxi	Taxi	Taxi	Taxi
1. Act. Baro. - inHgA		30.16	30.16	30.15	30.14	30.14	30.14	29.80	29.80	29.80	29.80
2. Spec. Hum. - lb/lb		0.0115	0.0115	0.0115	0.0105	0.0105	0.0105	0.0050	0.0050	0.0050	0.0050
3. Induct. Air Temp.-°F		73	73	73	126	122	120	62	62	62	62
4. Cooling Air Temp.-°F		73	72	72	112	103	99	60	59	59	58
5. Induct. Air Press.-inHgA		30.31	30.31	30.31	30.05	30.05	30.00	29.96	29.98	30.00	30.01
6. Engine Speed - RPM		1360	1365	1330	1350	1350	1340	1350	1360	1350	1350
7. Manifold Air Press.-inHgA		13.8	14.1	14.5	14.7	14.8	17.0	14.3	14.1	14.0	13.9
8. Induct. Air Density-lb/ft^3		0.0754	0.0754	0.0754	0.0680	0.0684	0.0685	0.0761	0.0761	0.0762	0.0762
9. Fuel Flow, W_f-lb/hr		18.7	16.5	14.7	19.0	17.0	15.5	22.6	20.7	18.7	16.5
10. Airflow, W_a-lb/hr		227.8	227.8	233.3	234.2	241.3	230.0	243.6	236.9	230.2	228.7
11. F/A (Measured) = 9 / 10		0.0821	0.0724	0.0630	0.0811	0.0705	0.0675	0.0928	0.0874	0.0812	0.0721
12. Max. Cht - °F		352	383	408	371	399	418	343	360	374	389
13. Avg. Cht - °F		317	335	357	330	349	356	306	313	321	332
14. Min. Cht - °F		261	251	265	263	261	258	256	248	252	261
15. EGT - °F		755	675	681	736	683	679	719	637	618	623
16. Torque, lb-ft		104	104	--	--	--	--	--	--	--	--
17. Obs. Bhp		18	18	--	--	--	--	--	--	--	--
18. % CO_2 (Dry)		8.94	10.61	12.51	8.84	10.23	10.35	7.30	7.96	8.91	11.04
19. % CO (Dry)		8.71	5.53	2.72	7.19	4.63	1.32	10.27	9.31	7.86	4.62
20. % O_2 (Dry)		0.37	0.63	0.64	1.59	1.87	4.72	0.50	0.36	0.36	0.35
21. HC-ppm (Wet)		5565	5342	3218	15,215	8178	9589	9258	5003	4124	3756
22. NO_x-ppm (Wet)		49	88	139	85	148	415	22	38	56	106
23. CO_2-lb/hr		31.0	35.3	41.6	30.9	35.9	34.0	27.6	28.8	30.8	36.6
24. CO-lb/hr		19.2	11.7	5.76	16.0	10.3	2.76	24.7	21.4	17.3	9.75
25. O_2-lb/hr		0.931	1.52	1.55	4.05	4.77	11.28	1.37	0.95	0.91	0.84
26. HC-lb/hr		0.802	0.742	0.466	2.247	1.193	1.316	1.481	0.764	0.599	0.523
27. NO_x-lb/hr		0.0132	0.0228	0.0360	0.0234	0.0405	0.107	0.0066	0.0108	0.0153	0.0276
28. CO-lb/Mode		5.118	3.124	1.536	4.271	2.758	0.736	6.584	5.716	4.614	2.599
29. HC-lb/Mode		0.214	0.198	0.119	0.599	0.318	0.351	0.395	0.204	0.160	0.139
30. NO_x-lb/Mode		0.0035	0.0061	0.0096	0.0062	0.0108	0.0284	0.0018	0.0029	0.0041	0.0074

TABLE C-21. ARITHEMATIC AVERAGING OF BASELINE (TABLE 5) DATA--TCM GTSIO-520-K ENGINE

Baseline No.	Avg. T_i - °F	Avg. ρ_i - lb/ft^3	CO lb/cyc.	HC lb/cyc.	NO_x lb/cyc.	Max. Cht - °F	Avg. cyc. F/A
1	72	0.0755	41.477	0.828	0.0552	417	0.0871
2	73	0.0754	43.879	0.649	0.0482	415	0.0861
3	74	0.0750	39.336	0.804	0.0587	421	0.0865
8	62	0.0762	44.747	0.675	0.0634	405	0.0878
9	62	0.0761	42.860	0.755	0.0644	415	0.0882
Total of 5	343	0.3782	212.299	3.711	0.2899	2073	0.4357
Avg. Cycle Data	69	0.0756	42.460	0.742	0.0580	415	0.0871
Avg. Emiss. - % of STD			232.4	89.8	8.9		
4	112	0.0700	41.447	1.113	0.0442	438	0.0880
5	117	0.0701	45.267	1.198	0.0393	426	0.0899
6	112	0.0705	43.720	1.342	0.0426	435	0.0898
7	116	0.0691	45.702	0.966	0.0502	418	0.0876
Total of 4	457	0.2797	176.136	4.619	0.1763	1717	0.3553
Avg. Cycle Data	114	0.0699	44.034	1.155	0.0441	429	0.0888
Avg. Emiss. - % of STD			241.0	139.7	6.8		

Note: The data presented above was grouped for arithematic averaging so that two basic ambient conditions could be evaluated on a generalized basis.